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Quantifying Permafrost Extent, Condition, and Degradation Rates at Department of Defense Installations in the Arctic

Christopher A.J. Edlund

QUANTIFYING PERMAFROST EXTENT, CONDITION, AND DEGRADATION RATES AT DEPARTMENT OF DEFENSE INSTALLATIONS IN THE ARCTIC

THESIS

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Abstract

The DoD is planning over $500M in military construction on Eielson Air Force Base (AFB) within the next three years. This construction program will expand the footprint of facilities and change parts of the storm water management scheme, which may have second order effects on the underlying permafrost layer. These changes in permafrost will drive engineering decision making at local and regional levels, and help shape the overall strategy for military readiness in the Arctic. Little site-specific knowledge exists on the human caused effects to permafrost at this location. In 2016, the permafrost degradation rates at Eielson AFB were modeled using the Geophysical Institute Permafrost Laboratory (GIPL) 2.1 model and limited available geotechnical and climate data. Model results indicated a degradation of the discontinuous permafrost layer at Eielson AFB of at least 7 meters in depth over the next century.

To further refine an understanding of the geophysics at Eielson AFB and help engineers and commanders make more informed decisions on engineering and operations in the arctic, this project established two long term permafrost monitoring stations near the future construction sites. The data set generated by these stations are the first of their kind at Eielson AFB and represent the first modern systematic effort in the DoD to quantify permafrost condition before, during, and after construction activities. In addition to better understanding the effects of construction activity, we hope to provide awareness and better stewardship for permafrost as a fragile and important natural resource present on many federally owned installations.

Through direct measurement and statistical analysis, the permafrost conditions at Eielson AFB were compared to other nearby permafrost monitoring stations owned and operated by the University of Alaska Fairbanks' Permafrost Laboratory. The direct measurement of the permafrost on Eielson indicates a temperature of -0.14oC at a depth of about 3m. The permafrost conditions on Eielson, when compared to the UAF data, vary in a statistically meaningful way, and therefore indicates that this area contains permafrost that is unique to this location, and warrants further future study.

Acknowledgments

I would like to thank the many individuals and organizations that contributed to the successful modeling and investigative field work that drove my thesis research. First, to my wife and children, who endured the long hours of study and multiple trips away from home for field work and presentation of the results. I would also like to thank Dr. Diedrich Prigge V for his leadership, mentorship, and friendship in accomplishing all aspects of this project. Further, I would like to acknowledge the humble and gracious advice that I received from Dr. Vladimir Romanovsky and Dr. Alexander Kholodov at the UAF Permafrost Lab. The information they shared was critical to the success of the field work and data analysis in this project. Last, I would like to thank the U.S. Army Corps of Engineers personnel, specifically Kevin Bjella, for their assistance in conducting the ERT and drilling operations in the field. They were critical in accomplishing the installation of the ground stations.

Christopher A.J. Edlund

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QUANTIFYING PERMAFROST EXTENT, CONDITION, AND DEGRADATION RATES AT DEPARTMENT OF DEFENSE INSTALLATIONS IN THE ARCTIC

I. Introduction

The cryosphere is the portion of the earth's surface that remains below freezing year round (National Snow and Ice Data Center, 2017a). The cryosphere is composed of frozen water located in oceans at the poles, and frozen ground. Frozen ground that has existed for two or more years is called permafrost (Van Everdingen, 2005). Cryospheric science centered around the study of permafrost has been active since at least the mid-1940s, although the military helped too add significant research funding and manpower to understanding construction methods on permafrost after World War II, because many new Cold War installations were constructed in the Arctic during that period. The study of permafrost in the military began in earnest in during the rapid military expansion between World War I and World War II. The Department of Defense (DoD), then known as the Department of War, needed to establish operations in the arctic to protect the mainland states from threats in the Pacific and Eastern Europe (Lott, Joyce, & Empson, 1984). Throughout this short history of study, much has been gained in the collection of data. The science of modeling and analyzing the frozen ground has also increased in popularity significantly, especially in the last two decades, as can be seen in Figure 1 (Scopus, 2017).

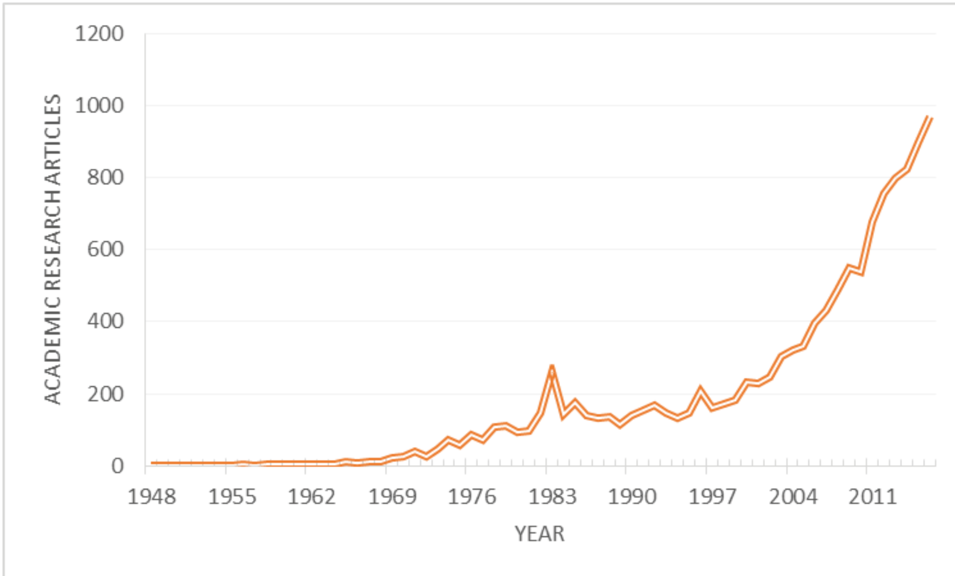


Figure 1: Number of Published Articles on Permafrost vs. Year

The cryosphere is changing in significant ways. The release of greenhouse gases (GHGs) has the potential to alter the way that our atmosphere traps and distributes heat, pollutants, and particulate matter (Schuur et al., 2015). Many government and non-government entities are now attempting to model and predict GHG and carbon emissions into the atmosphere, and correlate these models to global dynamic changes in temperature, hydrology, and climate. One set of model outputs is seen Figure 2. This International Panel on Climate Change (IPCC) graphic shows that many models predict increased anthropogenic carbon emissions over the next century. Changes in climate correlated to increased anthropogenic carbon emissions have begun to increase the rate at which significant stores of frozen water are melting into the oceans (Osterkamp, 2001). Ocean level rise, more popularly "sea level rise," has the potential to inundate man-made and natural features of the coastlines of some of the most populated places on earth (Isla, Marchandx, Division, & Catalunya, 1992). In the areas where permafrost is extant, rapid thawing is changing the strength and movement of soils (Arenson, Johansen, & Springman, 2004).

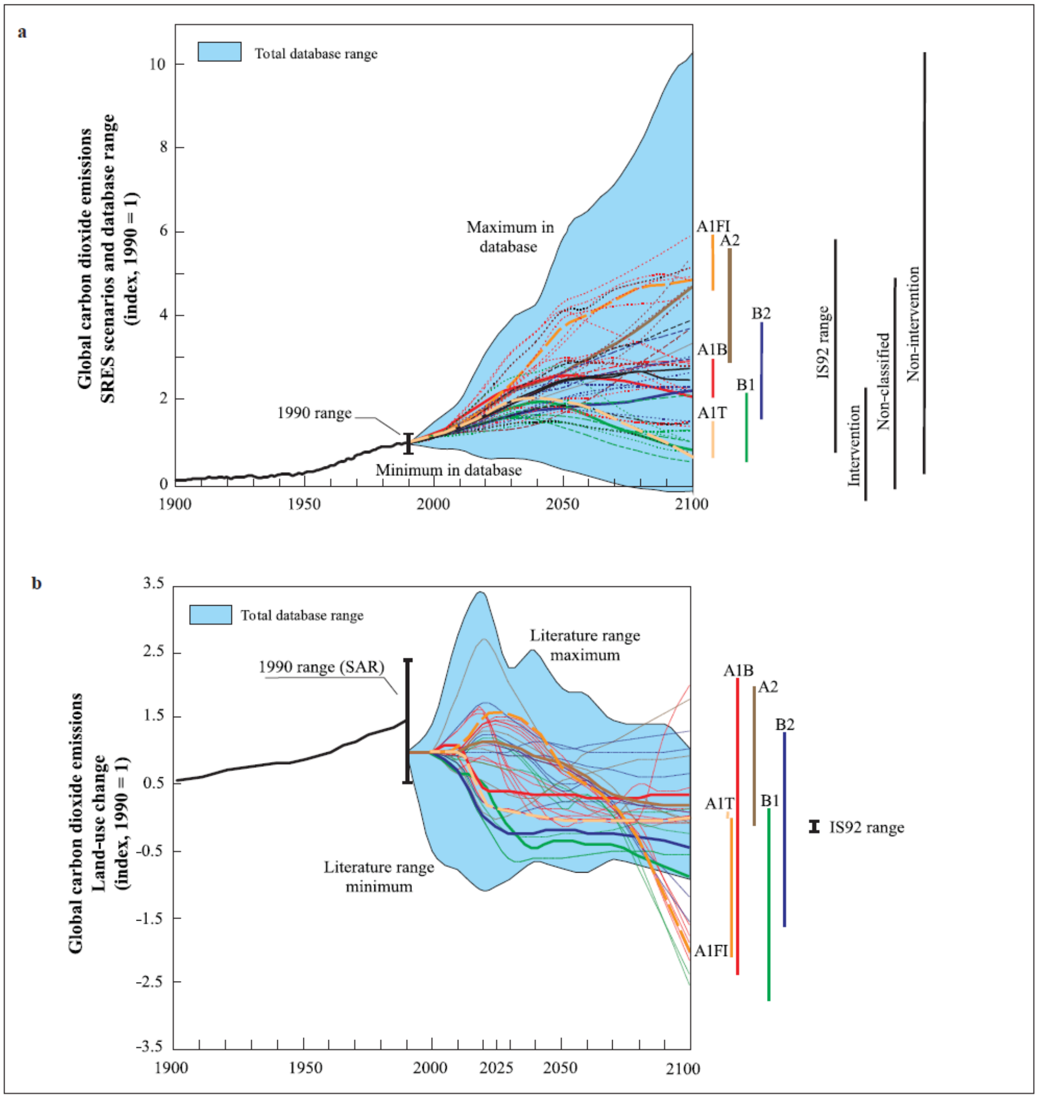


Figure 2: Global CO2 emissions related to energy and industry (Figure 2a) and land-use changes (Figure 2b) from 1900 to 2100

As the characteristics and extent of permafrost soils change, patterns of animal movement and plant growth are also shifting (Abbott, Abbott, Brochmann, &

Brochmann, 2003). Land mammals have traditionally followed food sources, and as the locations on earth that contain permafrost change, so do the types of animals that inhabit those areas (Hewitt, 2004). Scientists are studying changes in plant and animal ranges, growth patterns, and other characteristics. One example model is shown in Figure 3. In Alaska, this is most clearly seen in the historically dynamic migratory patterns of caribou and the humans who relied on them as a food source (McBeath & Shepro, 2007).

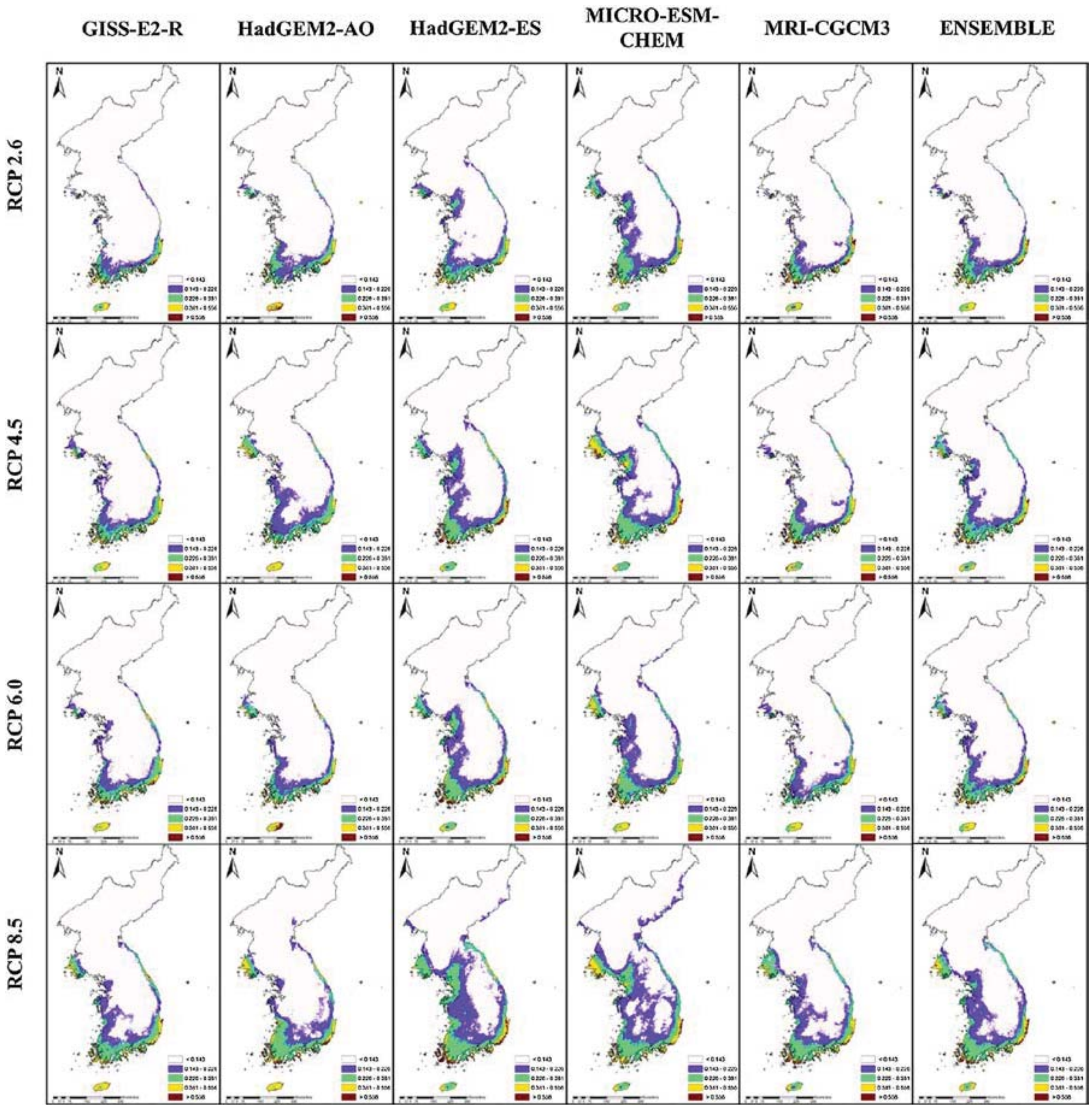


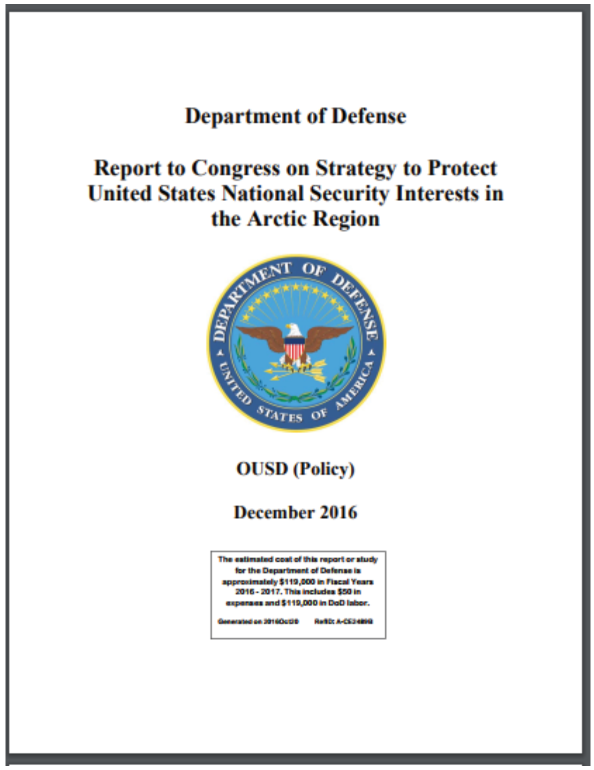
Figure 3: The future distributions of Silver Magnolia in 2070 under 20 climate change scenarios. (Koo et al., 2017)

From a human perspective, the degradation of permafrost has many implications as well. The primary food sources of people groups in the arctic may shift in a way that will make subsistence hunting and fishing inadequate to support the populations that exist now (McBeath & Shepro, 2007). These changes in food availability will increase the potential for food shortage, and in turn the potential for conflict.

In many ways, the degradation of permafrost has occurred in an almost imperceptible way. A single generation 100 years ago may have witnessed a single hundredth of a degree shift in the average permafrost temperature worldwide (Nakicenovic et al., 2000). The modern fact is that the permafrost on earth is changing at a rate greater than that seen over the past century. Historic permafrost health is observed using scientific methods that analyze atmospheric gas, organic content, and particulate matter that has been trapped in deep permafrost over thousands of years (J. Brown & Romanovsky, 2003). Though it may seem to the individual that these changes are insignificant, the shifting of such vast stores of GHGs, water, and energy will affect society and increase tension among all things that rely on earth-bound resources (Schuur et al., 2015). The most obvious way that man is affected by the thawing of the arctic is in the area available for habitation. Recently, transportation routes have opened that have not existed since man plied the seas (Stephenson, Smith, & Agnew, 2011). As more areas thaw, land will become inhabitable and natural resources that had been trapped in ice will be available. As thawing occurs, vast amounts of GHG (carbon) will be released, which will further accelerate the carbon cycle (Schaefer, 2015). Additionally, existing infrastructure will become vulnerable to both shifts in the natural landscape and shifts in social and political willpower (Borough, n.d.). Conflict has occurred already in areas that have seen flooding and significant natural disasters (Reuveny, 2007).

Problem Statement

In order to remain ready for future humanitarian and security requirements, and in order to operate its facilities in the most sustainable possible manner, the military must understand the rates and extent of changes to permafrost in areas where it affects military installations, infrastructure, and transportation routes. The official DoD strategy in the arctic is imprecise and lacks the directive clarity necessary for operational leaders to plan, budget, resource, and train for future operations in the Arctic. The DoD envisions "a secure and stable region where U.S. national interests are safeguarded, the U.S. homeland is defended, and nations work cooperatively to address challenges" (U.S. Department of Defense, 2016). Based on funding dollars, the military has not made as significant a commitment to understanding the geophysical changes that will continue to accelerate in importance to the security of our nation, relative to many other endeavors that have been undertaken such as weapons systems upgrades and new aircraft acquisitions.



Department of Defense

Report to Congress on Strategy to Protect United States National Security Interests in the Arctic Region

OUSD (Policy)

December 2016

The estimated cost of this report or study for the Department of Defense is approximately $119,000 in Fiscal Years 2016 - 2017. This includes $50 in expenses and $119,000 in DoD labor.

Figure 4: DoD Arctic Strategy Cover

In order to properly assess where the DoD is and where it needs to improve in its understanding of permafrost degradation, specifically in terms of facilities, infrastructure, and transportation, we must begin to gather concrete data that will aid in a more accurate understanding of how permafrost degradation is affecting, and will continue to affect, DoD facilities in the Arctic. This need is underscored by the immense investment in facilities, aircraft, and personnel that is occurring now at installations across the Arctic, including the bed down of F-35 aircraft at Eielson AFB.

Research Focus and Objectives

The intent of this research effort is to gather data that will aid in establishing long term installation planning and permafrost stewardship policy changes in the DoD. Once established, the dataset will be used for ongoing permafrost research in other fields like facility design. Outcomes of data analysis include the validation of previous permafrost models developed for installations and the characterization of permafrost soil conditions at Eielson AFB. The data will be useful to future research endeavors as well, specifically for refining Unified Facilities Code (UFC) guidelines and other similar Federal design criteria.

This research is focused on the effects to existing permafrost from anthropogenic activities and climate warming. The depth of permafrost and its temperature are the primary research focus areas, which will be combined with soil boring data and other geophysics models to provide a greater understanding of the total carbon, hydrological, anthropogenic, and climate impacts at the research site. The model outputs provide insight about where and to what extent permafrost currently exists in this geographic area of Eielson AFB, and whether or not there appears to be degradation related to the construction activity driven by new facility requirements. Follow on research efforts will determine the degradation rates of the existing permafrost.

Investigative Questions

Three primary questions will drive the methodology of the data collection for this research effort. These questions are 1) what is the depth and extent of permafrost on Eielson AFB, 2) what are the characteristics of the soils, and 3) how does the apparent existing degradation impact plans for future base expansion and land use? Using this data to validate Capt Graboski's model will be possible two to three years after the data collection begins. Multiple years of data are required in order to build a defendable degradation rate.

Methodology

To begin the data collection necessary to refine a strategy for the future, a ground temperature monitoring station was installed at Eielson Air Force Base (AFB), located near Fairbanks, Alaska. This site was selected due to the amount of new anthropogenic activity ongoing there (construction), and due to the availability of support resources in the local area to accomplish the study. The ground station was sited using Electrical Resistivity Tomography (ERT) surveys, as well as information gathered using frost probe measurements and collaboration with the local Civil Engineer Squadron. The monitoring station consists of a cased 2-inch boring to a depth of 10 feet. Within the boring, a string of temperature sensors has been affixed at various depths. A weatherproof data logger records the temperature at each depth every 60 minutes. The data gathered by the station will be used to characterize the permafrost on Eielson AFB, which will provide the first modern dynamic data set for ongoing permafrost research by the DoD and the permafrost science community at large through the Global Terrestrial Network for Permafrost (GTN-P). The data will be aggregated year over year, and used to build seasonal freeze/thaw curves for the soil. The shifting of the freeze/thaw curves either toward warmer or colder regimes will indicate the rate at which the ground and existing permafrost is changing in average temperature. These rates will then be compared to Capt Graboski's models from his research in 2017.

Assumptions/Limitations

Several limitations and assumptions are acknowledged by the research team. First, the site selection process was limited to areas on Eielson AFB that could be accessed without special escorts or that would impede upon airfield operations. Base personnel were not available to augment the research team. The site survey would be conducted in a narrow 10-day window, so the study was limited to the amount of work that could be accomplished during that time. The instrumentation and data logging equipment is limited to the lower quality end of what is available on the commercial market, due to a very limited budget of about $15,000 for research, travel, and equipment. This may degrade the service life of the equipment, and necessitates an annual maintenance and data collection visit in order to ensure the long term operation of the stations.

Implications

Without a generalized knowledge of permafrost conditions at installations in the Arctic, the DoD will not be able to coherently address any facility or mission changes necessary to adapt to a changing climate. At this time, DoD engineers are using models and data developed using rudimentary processes in the 1950s – 1970s (UFC). These models and data sets are generalized, and do not provide military engineers with the site-specific knowledge necessary to make recommendations to local commanders for future planning and mission needs.

Preview

The remainder of this document will follow the standard AFIT academic thesis layout. A brief summary of the state of current permafrost research is presented. The methodology implemented for the data collection portion of the field research is outlined, and an assessment of data quality and recommendations for future research is also given.

II. Literature Review

The purpose of this chapter is to outline the status of worldwide cryospheric research as it relates to permafrost degradation. The chapter provides an overview of the important ongoing research efforts related to permafrost and Arctic construction from a worldwide, regional, and DoD specific perspective.

Worldwide Permafrost

Permafrost is perennially frozen ground that has existed for two years or more. Permafrost represents about 24% of the exposed land in the earth's Northern Hemisphere, and 80% of the land surface in Alaska (National Snow and Ice Data Center, 2017b). Permafrost exists in the Southern Hemisphere across the entire exposed land area of Antarctica, and some isolated areas in Patagonia and New Zealand's Alps. Much less is known about the Southern Hemisphere permafrost due to remoteness, accessibility issues, and the large sheet of ice that covers most of Antarctica. Where and how fast permafrost is formed and degrades depends on mean annual air temperature, annual snow depth, and several other climatological and geophysical properties (Schaefer, Lantuit, Romanovsky, & Schuur, 2012)

Alaska permafrost soils in the Arctic are warming almost every year, based on historical yearly temperature data (Nakicenovic et al., 2000). The top of the permafrost table in many areas is lowering in depth incrementally, and the active layer thickness is in turn increasing in depth. While this truth applies almost everywhere where permafrost soils exist now, an extremely accurate degradation rate cannot be presently determined or projected in a meaningful way independent of the location of interest (Cable, 2016).

Location of interest must be known because several variable factors are important to model and predict future degradation rates. The area of science or engineering in which the permafrost model will be used will drive what type of modeling information is most important. An engineer and a climatologist will care about different things when modeling melting permafrost, and there are inherent tradeoffs in accuracy any time one is developing a model (Nicolsky, Romanovsky, & Tipenko, 2007; Stendel et al., 2002).

One must know annual precipitation types and quantities, insolation intensity maximum and aggregate totals, and myriad soil properties. If this information can be accurately quantified using historical data, then fairly accurate modeling can be conducted (Zheng, Hunt, & Running, 1993). Current modeling techniques can consistently depict actual permafrost conditions to within ±0.14 m of thickness and 5ºC temperature accurately, depending on how much information is known about a particular site of interest and which of the IPCC climate models is being utilized (Nicolsky, Romanovsky, Alexeev, & Lawrence, 2007).

With an accurate model output, it is possible to predict future permafrost degradation or growth. The most common technique to model future states of permafrost relies upon data from a climate model and holds other important variables constant. The primary changing factors for the analysis are the outdoor air temperature and precipitation levels. The soil characteristics and most hydrologic factors are considered relatively static when compared to the popularly understood changing climate factors (Romanovsky & Osterkamp, 2000; Y. L. Shur & Jorgenson, 2007). Several studies in northern Alaska have shown predicted degradation rates of between 0.02 and 0.04 m per year over the next century (Lemke et al., 2007).

In addition to direct measurement and climate effect modeling, scientists are beginning to study the effects of hydrology on permafrost thawing. In some vulnerable areas of the Arctic, a single hydrological event may cause more thawing in one day than decades of small scale mean annual air temperature increases (Romanovsky & Osterkamp, 2000). The difference in energy intensity between liquid water and ambient ground level air illustrates how these two mechanisms of permafrost change are dissimilar in their thawing abilities. The specific heat of water is about four times greater than that of air, meaning it can carry four times as much energy per unit volume into the ground. Water is also able to penetrate the active layer much more effectively than air (Smith, 1996a). Evidence of large scale, rapid permafrost degradation from precipitation is somewhat anecdotal today, but the effects of ocean water causing rapid degradation are well documented (Osterkamp, 2001; Stephenson et al., 2011). Some leading permafrost research engineers anticipate an increased focus on the hydrological effects on thaw rates of permafrost (Romanovsky & Osterkamp, 2000). The Cold Regions Research and Engineering Lab in Fairbanks has several professional engineers dedicated to quantifying the future possibilities related to water-induced thawing in permafrost (Bjella, 2017).

With degradation from air temperature increases and hydrological changes almost certain, the effect of melting permafrost on the rest of the world's climate is notable. Melting permafrost will not only affect areas where permafrost exists, but will add to the overall global change climate happening now. One of the most critical outputs from permafrost degradation in the Arctic is the release of Greenhouse Gases (GHGs) that have been trapped in the ice for thousands of years. The GHGs are left over from decayed organic matter and atmospheric gases that became trapped during permafrost formation (Koven et al., 2015). As GHGs are released from formerly frozen ground, the GHGs mix with the greater atmosphere through polar wind currents and cause an increased potential for climate warming. This, in turn, causes permafrost degradation to increase in pace, which releases even more GHGs. The feedback cycle from released GHGs, particularly CO_2 and methane, will likely be one of the most significant contributors to the warming climate, aside from human activity (Schuur et al., 2015).

Permafrost in Alaska

Permafrost in Alaska suffers from the same degradation modes as permafrost elsewhere in the world and presents similar potential negative consequences if thawing continues unchecked. Alaska permafrost is generally extant in areas where thick layers of organic matter have accumulated on top of ancient riverbeds, known as syngenetic permafrost. Figure 5 summarizes the status of permafrost and geology in Alaska. Syngenetic permafrost is formed as the insulating layer of sediment and organics is deposited. As deposition occurs, the active layer of the ground decreases in size, and the permafrost table becomes more shallow because it is now more effectively insulated (Shur, French, Bray, & Anderson, 2004).

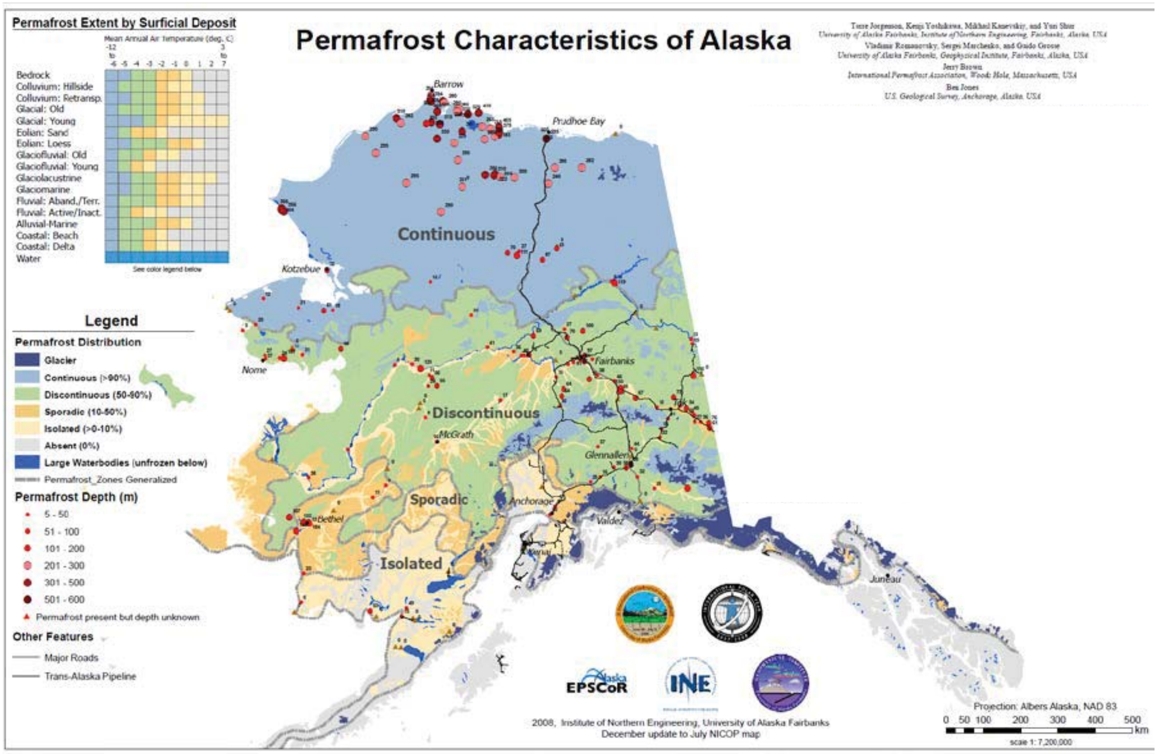


Figure 5: Permafrost Characteristics of Alaska

Epigenetic permafrost growth occurs when the bottom of the permafrost layer is lowered as a result of some discrete or seasonal cooling event (Van Everdingen, 2005). This type of permafrost growth happens (or, in a more contemporary sense, *happened*) when ground ice formed after the ground material was already in place. This contrasts with syngenetic permafrost in which the permafrost layer formed as soil was being deposited. Epigenetic permafrost is commonly seen in the form of ice lenses or wedges underground. The lenses and wedges occur in areas where the moisture content of the soil is considered ice-rich. This ground can be defined similarly as thaw-sensitive, in that it will undergo thaw settlement due to a loss of mechanical strength during thawing. Ice-rich permafrost is generally considered permafrost in ground where moisture content “exceeds the total pore volume that the ground would have under natural unfrozen conditions” (National Snow and Ice Data Center, 2017a).

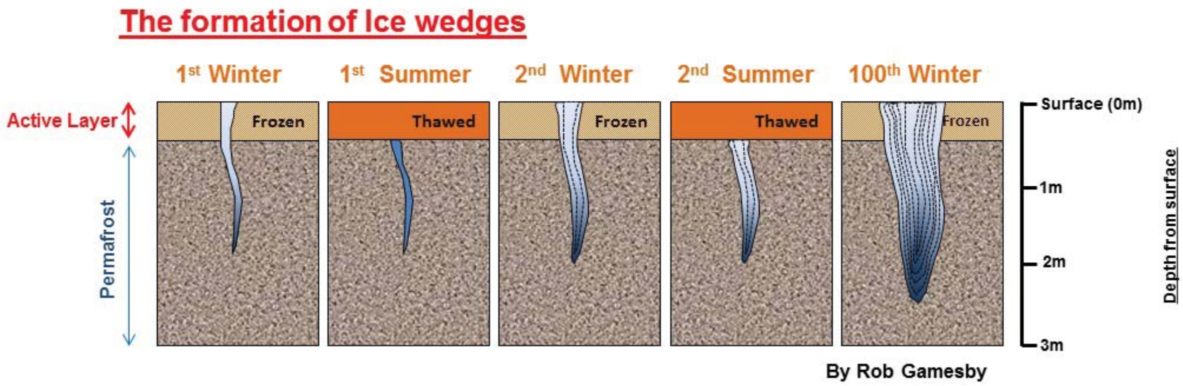


Figure 6: The Formation of Ice Wedges (Gamesby, 2015)

The two primary types of permafrost in Alaska exist to varying degrees depending on latitude. Above the Brooks Range of mountains in Northern Alaska, permafrost is almost entirely continuous. Permafrost in the continuous zone is composed of deep (>50 m) syngenetic permafrost overlain with more shallow epigenetic permafrost. Between the Brooks Range and the Alaska Range, permafrost is discontinuous (Jerry Brown, 2008). In the discontinuous zone, permafrost is at or near freezing and is therefore most at risk of near-term melting from climate change and anthropogenic activity (Nakicenovic et al., 2000). In terms of geological history, anything less than a scale of thousands of years is relatively quick, so a poorly designed facility melting a significant amount of permafrost in one decade might be considered quite rapid (Bjella, 2017).

Although epigenetic permafrost is more susceptible to thaw strain than syngenetic permafrost, both types of permafrost, when thawed, cause problems for engineers (Smith, 1996b). Competent engineers almost always consider existing permafrost when designing structures in Alaska, because in most populated areas the permafrost is already so close to the freezing/thawing point that any small human-caused interruption in the ground composition, climate, or hydrology could melt the permafrost in a matter of years (Bjella, 2017).

Figure 7: Thaw Settlement of a Home in Fairbanks, AK (Image Courtesy Syngen Consulting)

Several techniques are used to mitigate permafrost degradation. A common thaw mitigation method used in facility construction is insulating the ground prior to construction as shown in Figure 8 ("Cost and Constructability of Permafrost Test Sections Along the Alaska Highway, Yukon," 2009).

Figure 8: Ground insulation panel installation at thaw susceptible roadway project

(Wisner, 2015)

Completely preventing large scale permafrost degradation from climate warming induced thawing is not currently considered possible. Some scientists hypothesize that through a systematic change in the way that human activity operates upon the planet the degradation rate from climate may be slowed (Schaefer et al., 2012). Hydrological considerations are most important along the northern coasts, away from where the largest concentrations of military infrastructure and cities exist. Many military facilities do exist on the coasts of Alaska, but these facilities are isolated, small (often uninhabited), and require site specific strategies for successful permafrost thaw mitigation. Figure 9 depicts the relative population distribution in Alaska, with information aggregated from the United States Census Bureau and the Alaska Department of Labor Statistics. Figure 10 depicts military installation locations within Alaska. The primary installations are located in interior and southern Alaska.

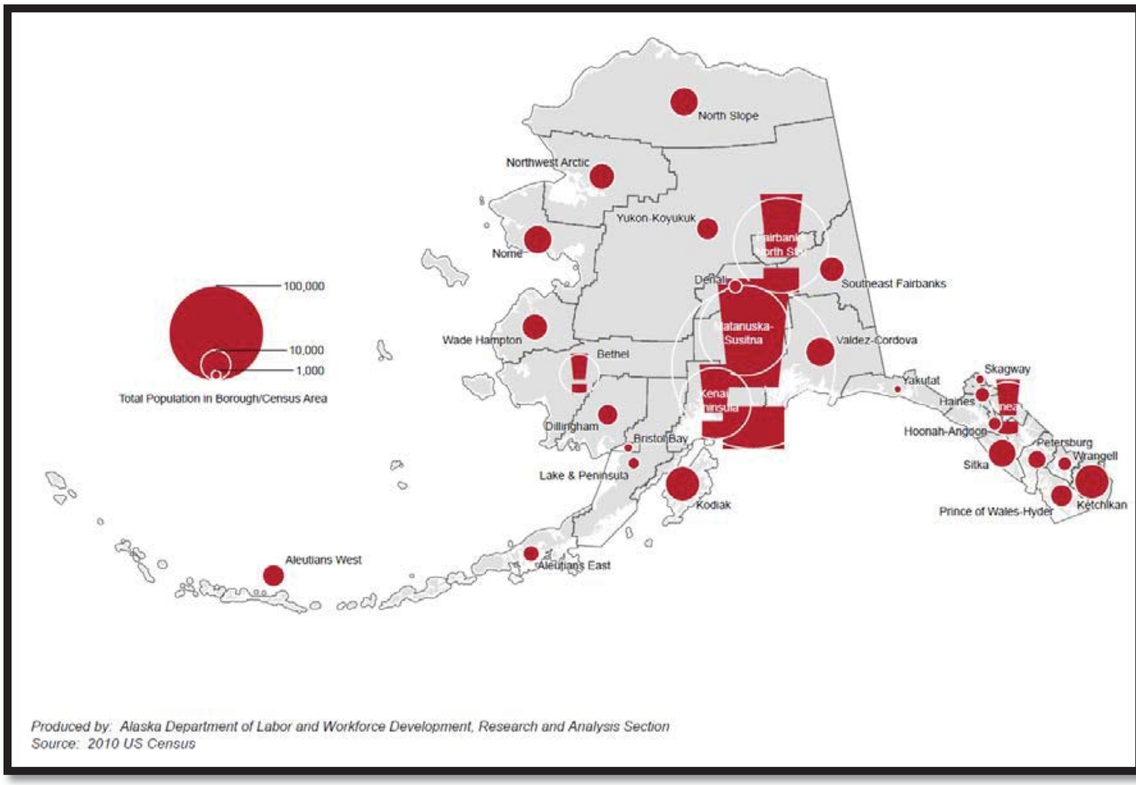


Figure 9: Population Distribution by Borough

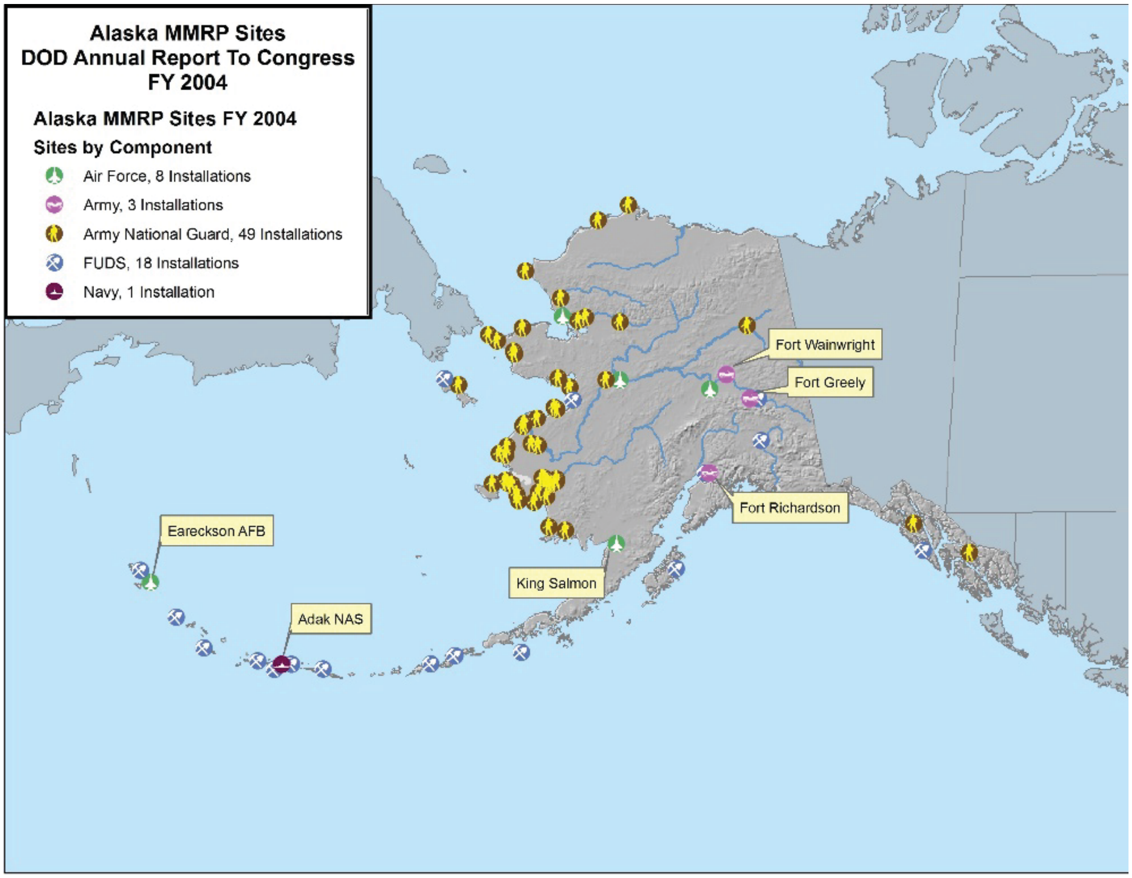


Figure 10: Location of Several Current and Former Military Installations in Alaska

The DoD does not have a unified strategy for anticipating or operating within the realm of future permafrost degradation in Alaska. Each installation has engineered facility and infrastructure solutions in an ad-hoc manner since the turn of the 20th century. History has proven to the military engineering community that permafrost must be considered before, during, and after construction of any facility that is sited in a permafrost zone, even if not sited directly on top of permafrost soil.

During the construction of the Alaska-Canada Highway (ALCAN), engineers did not understand how their construction activities would interfere with the fragile layer of soil and organics protecting the underlying permafrost in many sections of the road's pathway. The highway was built – literally ripped – through the forests and across the tundra of northern Canada and Alaska in less than one year. The effects of thawing permafrost on this hastily constructed transportation route are still experienced by anyone who drives the ALCAN. Academics and transportation engineers are still refining repair techniques to detect, mitigate, and in some cases slow the thawing of permafrost ground beneath the highway ("Cost and Constructability of Permafrost Test Sections Along the Alaska Highway, Yukon," 2009; Panda, Prakash, Solie, Romanovsky, & Jorgenson, 2010).

Figure 11: Historical photos of ALCAN construction (Library of Congress)

Learning from this example, the United States Army Corps of Engineers established the Cold Regions Research and Engineering Laboratory (CRREL) to study permafrost in earnest. The CRREL's primary mission in its first years of experimentation in Alaska was to hone the DoD's understanding of permafrost and seasonal frost, and apply that knowledge in novel ways to construct reliable and resilient facilities in the Arctic (Lott et al., 1984). The CRREL continues this mission today, with hundreds of papers published over a span of more than 50 years.

After the military, the next most interested user of permafrost-underlain land in Alaska is the consortium of oil companies that discovered oil in Prudhoe Bay in the late 1960s. The consortium built the Alaska Pipeline between 1974 and 1977 for the sole purpose of exporting oil to market. The most significant underground engineering obstacle for the builders of the pipeline was permafrost. Along its route, the pipeline uses several strategies for avoiding permafrost degradation. The pipeline is ballasted under concrete, insulated almost entirely, and in some sections, is elevated above the ground (Lenzner, 1977).

Figure 12: Alaska Pipeline construction in 1976

These strategies work together to keep frozen ground frozen, and ultimately protect the pipeline from damage that could result in a massive crude oil spill. Unique to pipeline construction at the time was the inclusion of thermosiphons within the elevated sections of the pipeline. The thermosiphons use inert carbon dioxide in a phase change state to cool the Vertical Support Members (VSMs) along the elevated portions of the pipeline. Because the oil flowing through the pipeline is maintained above 100ºF, the VSMs must be cooled to prevent heat transfer directly into the ground, which would thaw permafrost. The VSM thermosiphons have proven reliable and have been adapted for use in facility foundation design, road bed design, and other applications (Zarling & Haynes, n.d.). In response to the lessons learned from building the pipeline, several city and borough governments require new infrastructure to follow strict engineering philosophies and specifications when constructing facilities in permafrost zones (North Slope

Borough, n.d.; Wiggin, 2012). The DoD does not have policy or planning guidance at this time regarding the systematic analysis of permafrost degradation rates or mitigation strategies related to military construction in the Arctic.

Permafrost Research in Academia

It is evident that permafrost research in modern times is driven primarily by evidence that climate warming is occurring. The warming climate has an amplified effect in Arctic regions; it has a positive feedback loop as GHGs are released from melted permafrost and sea ice (Koven et al., 2015). Engineers must be cognizant of the fact that thawing permafrost ground will affect infrastructure and other facilities in negative ways unless proper design and construction techniques are utilized.

Several efforts are underway to simply gather all known permafrost meta- and micro-data into one place. The most unified effort for data collection and synchronization followed the international polar year conferences in 2009. The Global Terrestrial Network for Permafrost (GTN-P) was established as a database for permafrost scientists, but also for climatologists and oceanographers. The stated intent of the GTN-P is to allow communities outside the realm of geophysics to access up-to-date data related to changes in permafrost so that useful correlations can be revealed across scientific domains (Biskaborn et al., 2015). The goal of data collection and centralization is well underway and will continue.

Several universities with well-established geophysics labs specialize in permafrost research as well. The University of Alaska Fairbanks hosts the Geophysical Institute, of which the Permafrost Laboratory is a part. Several faculty and student research staff operate the Permafrost Lab. The Permafrost Lab's primary focus is the modeling of permafrost soil through direct measurement and mathematical modeling. The permafrost lab has used aerial imaging, ground penetrating radar (GPR), electrical resistivity tomography (ERT), frost probes, long-term ground temperature monitoring stations, and other methods to positively identify and characterize permafrost throughout Alaska and the wider Arctic (Osterkamp & Romanovsky, 1999). The Permafrost Lab is one of the most prolific research labs dedicated to this line of research, and all the research funded through the lab has concluded that permafrost is melting at an accelerating rate across the Arctic. The rate of degradation in Alaska is fastest in the wettest and hottest parts of the state. The areas above the Brooks Range are cold enough now to last for several more years, but human interaction coupled with a warming climate in the discontinuous permafrost zones will cause an increase in permafrost degradation. The discontinuous permafrost zones should be the focus of future study, with increased resolution in areas of interest (Cable, 2016).

The Air Force Institute of Technology began researching permafrost from a modeling perspective in 2017 (Graboski, 2017). The research effort was initiated due to the immense construction program planned for Eielson AFB. The base is a bed down location for two new squadrons of F-35 aircraft (Miller, 2016). The introduction of this new mission to Eielson AFB illuminated a permafrost understanding gap that had not been fully appreciated prior to the bed down decision (Department Of The Air Force, 2016). Although engineers have characterized permafrost conditions for specific construction projects, there is little comprehensive information available to engineers regarding existing permafrost extent, depth, or degradation rate near the area where the F-35 bed down will occur. Having a holistic view of the permafrost soil in the areas of heaviest construction will aid designers and base planners select the best sites for utility infrastructure, roads, and facilities. The wider permafrost science community will also gain from Eielson AFB permafrost data. The GTN-P currently has a gap in monitoring sites that spans almost 60 miles between Fairbanks and Delta Junction, AK (Biskaborn et al., 2015). This stretch of land is known for its negative effects on highway and electrical infrastructure. Establishing a data set to represent a midpoint between the monitoring sites in Fairbanks and the sites in Delta Junction, depicted in Figure 13, will add much needed resolution to the GTN-P network, to the benefit of all who utilize the data therein for scientific research.

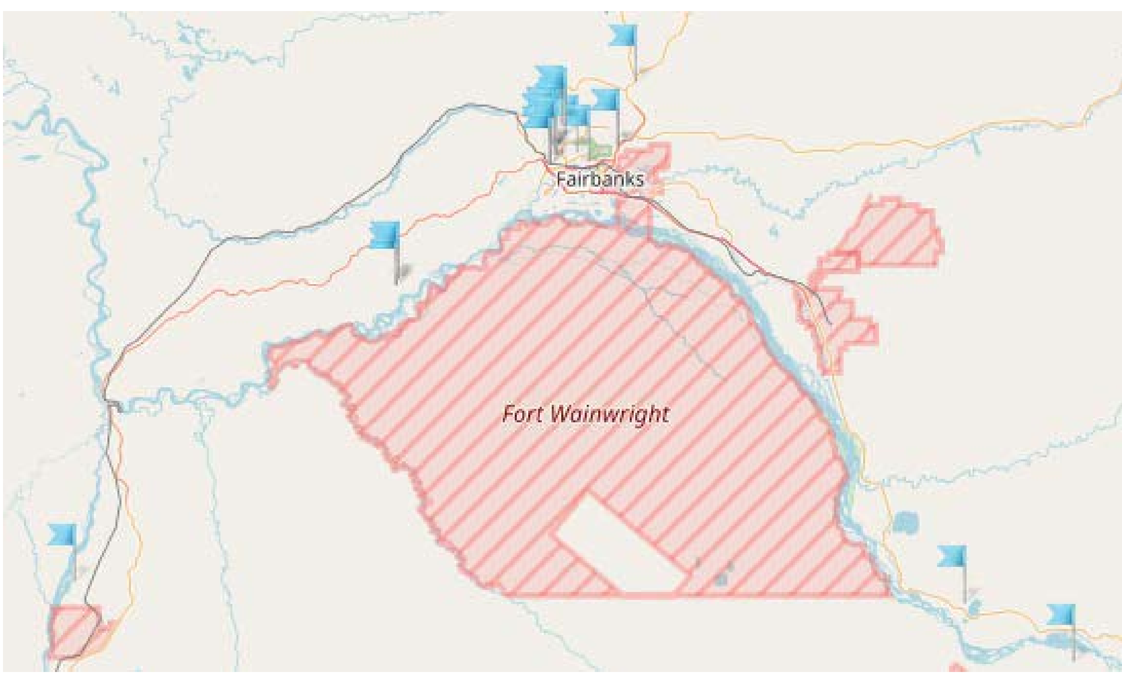


Figure 13: Map of GTN-P sites near Eielson AFB, AK (Blue Flags)

III. Methodology

To best quantify the rate of change of permafrost at Eielson AFB, the research team performed field work in order to gather data directly from the site of interest and to establish long term data collection stations.

Graboski (2017) had modeled permafrost degradation at two dissimilar locations on Eielson AFB without the benefit of any actual field data. Graboski relied heavily on the UAF Permafrost Lab GIPL model to provide an output dataset of ground temperature over approximately one century. Graboski's model relied upon soil data, climatological data, and foundation design drawings to anticipate the permafrost degradation from facility footprints. Graboski modeled a large facility footprint and the resultant permafrost degradation, as well as a small facility footprint and resultant permafrost degradation. These models provided insight and confirmation that permafrost degradation was likely at Eielson AFB if heated facilities were constructed without proper permafrost protection measures built into the foundations.

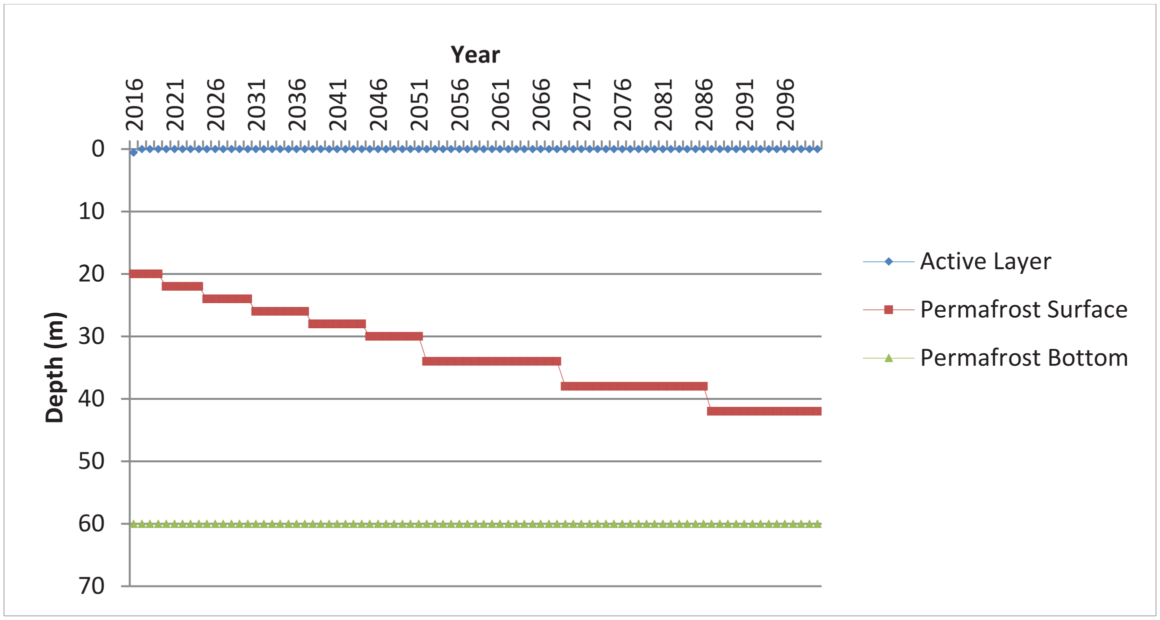


Figure 14: Large, Heated Facility Permafrost Degradation Projection Model

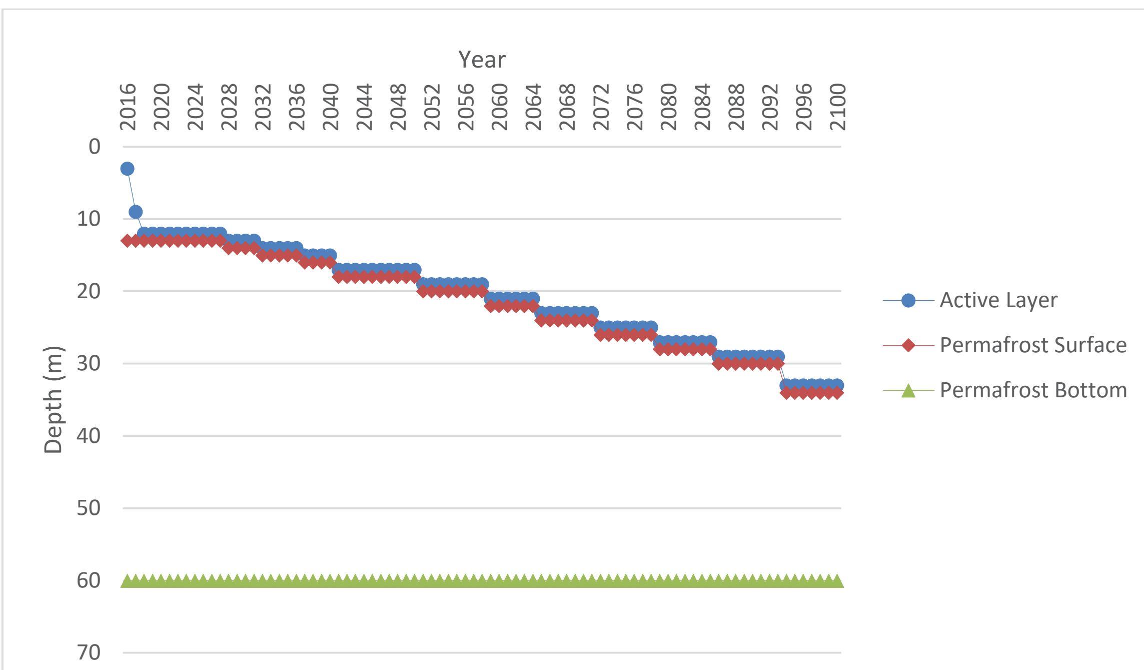


Figure 15: Small, Heated Facility Permafrost Degradation Projection Model

To establish an "accurate to reality" set of field data for analysis, soil data was collected and two monitoring stations installed for future use in future research. The DoD has many installations and remote facilities located in the Arctic. The most easily accessible installations to the researcher are in Alaska. There are two primary Air Force installations and three primary Army installations. Joint Base Elmendorf-Richardson is located in Anchorage, AK, and is an Air Force led joint base. This set of installations was not a relevant choice for this research due to its lack of permafrost resources. Fort Greeley, located in Delta Junction, is also located in a region where permafrost existence is considered sporadically discontinuous. The last two primary DoD installations in Alaska are Fort Wainwright and Eielson AFB. Fort Wainwright is directly adjacent to Fairbanks, while Eielson AFB is located approximately 26 miles from Fairbanks to the Southeast along the Richardson Highway. Both of these installations are located within a discontinuous permafrost zone, but permafrost is less sporadic than other installations further south. Eielson AFB was ultimately chosen for further research due to accessibility to the research team, the impending F-35 bed down (as the primary major anthropogenic activity), and because prior modeling was focused on sites nearby (Graboski, 2017).

Within Eielson's boundaries, several areas contain surface elevation and flora indicative of existing permafrost. Black spruce forest and upland hills are some of the most prominent indicators of the existence of permafrost on Eielson AFB. In other areas, polygonal ground and uneven settlement can also indicate the existence of permafrost. Aerial imagery proved helpful in understanding where large stands of undisturbed (but still accessible) black spruce existed on the base. Since most new anthropogenic activity is projected to occur on the South Loop of Eielson AFB, black spruce stands in that area were most interesting as potential research locations. Prior to arriving at Eielson, four potential transects were selected for further investigation in person.

Figure 16: Initial Survey Transect Locations

Once at Eielson, the team conducted in-person site surveys with the USACE CRREL team. The first site was found to be essentially a swamp. There was extensive standing water and tussocks at this location. Due to the standing water, this site was not possible for use, since the GPR and ERT surveys require a dry ground surface. The GPR equipment also will not be effective if towed across rough terrain.

The next two sites visited (transects 2 and 3) exhibited many of the same attributes, with sections of standing water and terrain that varied in elevation more than 50 cm. The last site visited appeared to be an old jeep trail that had been abandoned at some point in the past. The trail section appeared to have a balance between disturbed and undisturbed areas, with the density of the tree cover varying from spacing of less than one meter to several meters. This site was usable, but not ideal. The team transited the area immediately surrounding the trail until a final site was discovered that was closer to the South Loop construction area than had been previously thought possible. The final site selected for investigation is pictured in Figure 17.

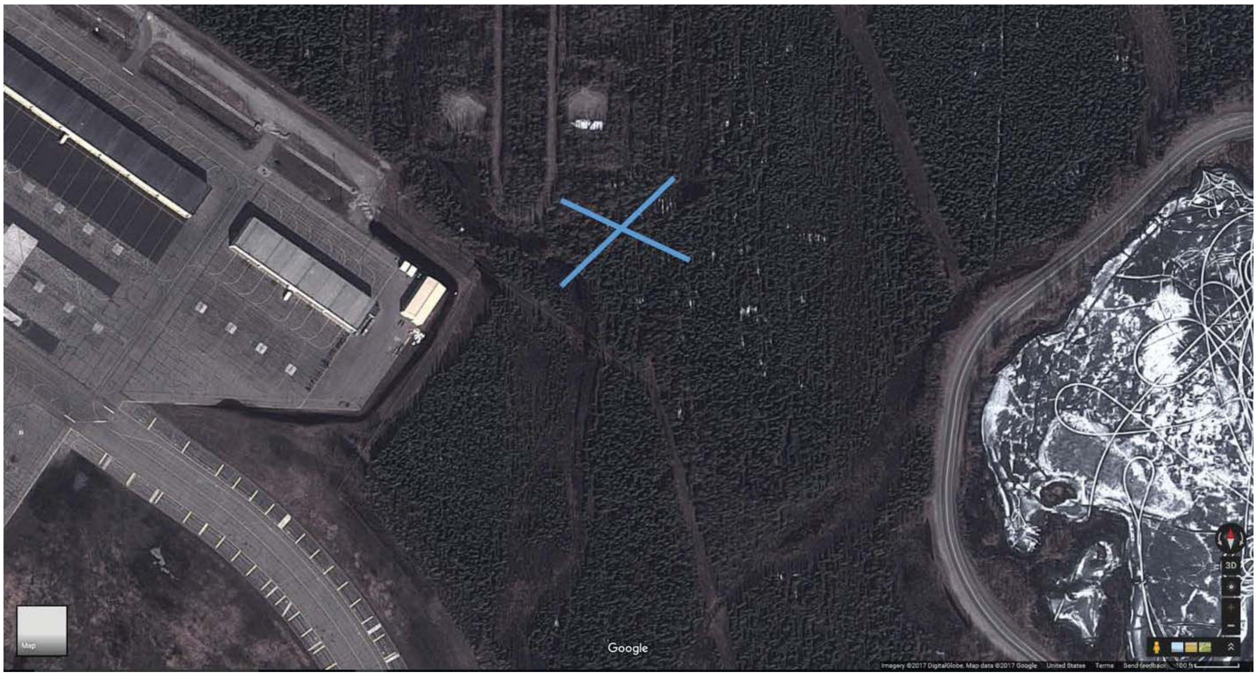


Figure 17: Transect locations used for ERT and drilling.

Figure 18: Detail View of Transect Locations

A GPR survey was not conducted due to time and resource constraints during the field investigation portion of the data collection. The GPR results would have been used to verify ERT findings. A GPR survey would have been difficult to carry out in a value added way due to the amount of deadfall trees, brush, and uneven land that would have required preparation prior to collecting GPR data.

An ERT survey commenced the same day as site selection. Because the depth interest was the top of the local permafrost table, the ERT was configured for monitoring at a maximum depth of 33 m using a 2-m horizontal spacing scheme for the electrodes. A total of 84 electrodes created a total transect distance of 168 m end-to-end. The electrode transect was established by hand, using a 100 m tape measure and survey marking flags. After flag placement, the transect was surveyed using handheld GPS equipment. Stakes were then driven into the ground and connected to the passive electrode cable via steel alligator style clips. The electrode cable from each half of the survey transect terminated into a multiplexing relay box, which was then connected to the ERT meter. The ERT meter was programmed for the transect spacing with a scaling factor of 2 m and set to generate a two-dimensional image. A contact resistance test confirmed that all connections from the electrode cable to the electrodes were below 5 kΩ-m.

Figure 19: ERT Probe Layout

Figure 20: ERT probe with jumper cord for connection to sensor cable.

Figure 21: AGI Super Sting R8 IP ERT Meter Used for Survey

The first transect was surveyed over the course of 176 minutes. The second transect, offset by approximately 80°, was set up in the same manner as the first transect. All data from both surveys were pulled into the EarthImager 2D® inversion modeling software. The software allowed the data from both ERT surveys to be analyzed for acceptability. No anomalies were discovered in the "whisker plot" of the data.

With all data verified for usability, a two dimensional image was generated for each transect data set. The output shown in Figure 22 is indicative of the results expected. Areas of differing resistivity are shown using a color scale. These images gave a virtual representation of the resistivity of the soil directly below the transect lines, akin to an MRI image used in hospitals.

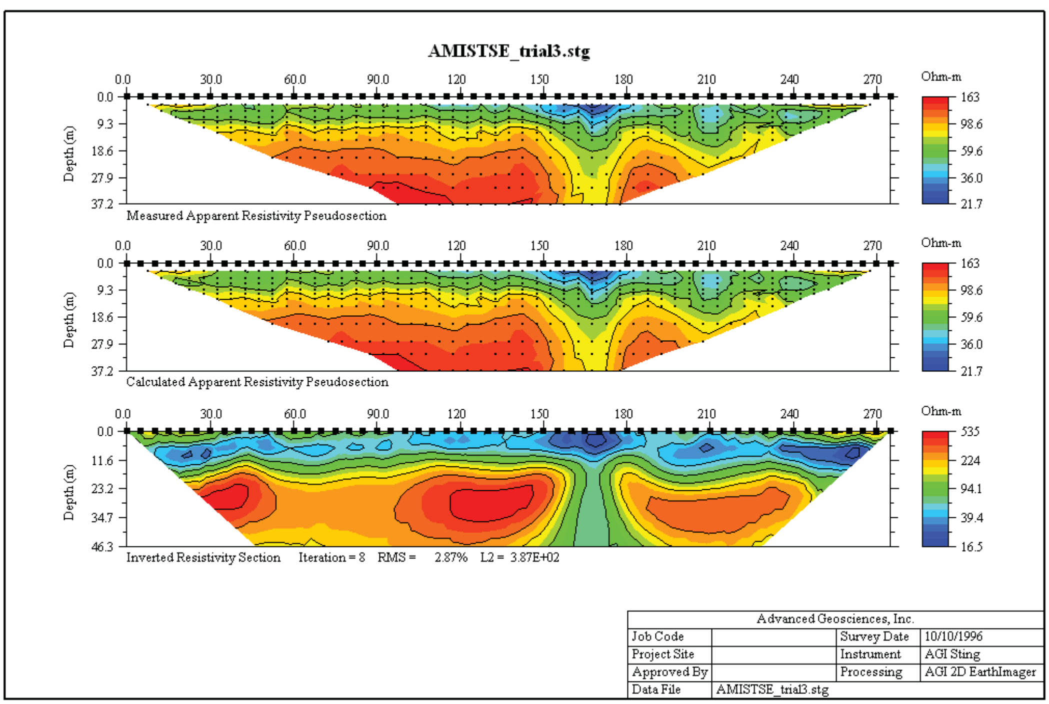


Figure 22: Example ERT Inverse Plot Output Using AGI EarthImager 2D

To add fidelity to the information gleaned from the ERT surveys, a frost probe survey was conducted. The frost probe was inserted into the active layer at the same general locations as the ERT probes. The distance from ground surface to refusal was recorded for each point, and recorded by hand. Frost probe measurements would give a general indication of the frost line in the soil, and would assist in verify the ERT results.

With two locations of interest, the next step was drilling into the soil and collecting soil samples for analysis. The first borehole was drilled using a direct drive hammer drill rig, branded as the Geoprobe 7822DT. The 2” hollow drill pipe was used, with acrylic core sample sleeves. This drill pulls 5’ sections of soil per sample, so two rounds of drilling were required per hole. Permafrost was struck at just under 9’ depth, so the hole was finished at 10’. Complications during drilling prevented complete soil sample results from the first borehole – the drill sleeve was impacted into the drill bit to a degree that it could not be removed without disrupting the soil within the sleeve. The second borehole was drilled to a depth of 10 feet, with samples photographed and annotated within each visible strata of ground.

Immediately after drilling completed, a PVC sleeve was installed in both holes to case the borings. The casings consisted of a capped 2.5” PVC electrical conduit section. At the ground surface, the casing was capped with an electrical pull box “LB” type fitting. The elbow was terminated into a 1’ x 1’ weatherproof storage box as shown in Figure 25.

Figure 23: Drill Rig

Figure 24: Example Soil Sample from Station 2

Figure 25: Station 2 Casing Layout

To record ground temperature data into the future, instrumentation was installed into the boreholes. The most important temperature measurements for determining permafrost degradation occur within the active layer. Thermistors were placed in the active layer at close interval, with the interval between thermistors widening as depth increased. The deepest thermistors were embedded within the permafrost layer. By collecting temperature data in the boreholes over a series of years, the permafrost depth can be shown graphically as it moves deeper into the ground. A typical trumpet curve for permafrost ground that is similar to the ground conditions at Eielson is shown in Figure 26.

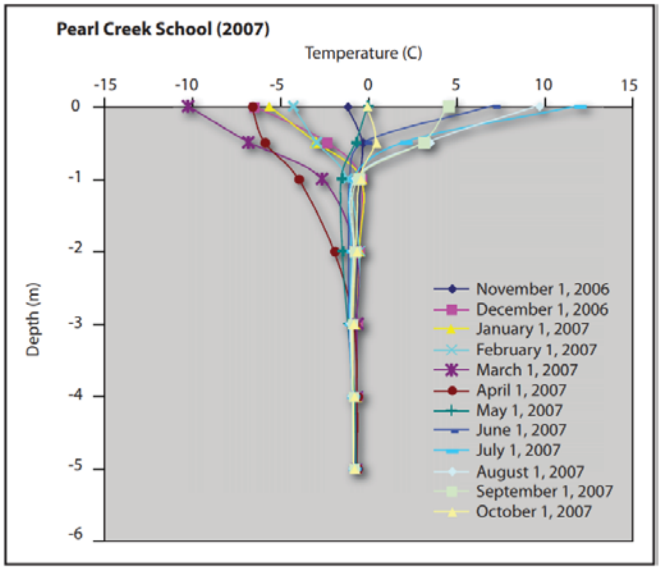


Figure 26: Example trumpet curve from Pearl Creek School in Fairbanks, AK

The thermistors used are OnSet HOBO SmartSensor thermistors, with various cord lengths. A total of nine thermistors were installed in the first monitoring well, which will act as a control point. Station 2 will be primarily affected by the changing climate only. Station 2 has fewer thermistors as a matter of funding constraints. Station 1 is composed of 11 thermistors, one soil moisture probe, and a combined ambient air temperature and relative humidity sensor. Monitoring station layout and components are depicted in Figure 27, Figure 28, Figure 29, Table 1, and Table 2.

Data logging is accomplished using a single HOBO H21 USB logger at each station. The data logger and expansion boxes are seen with excess cabling from the thermistor string in Figure 28. Soil moisture probe is installed directly adjacent (above) this box. Expansion port boxes are used to allow up to 15 channels at each location, with space for future expansion if research requirements change.

Data from the data logging equipment will become relevant after multiple years of collection. Seasonal temperature and precipitation variation make meaningful analysis difficult without at least a few years of data. For the purposes of this research, the small dataset generated in the month of August 2017 will be compared statistically to other permafrost monitoring stations within the area surrounding Eielson AFB. A simple fit test will be used to conduct a hypothesis test against other National Weather Service data and demonstrate the viability and accuracy of the monitoring stations for long term measurement.

Figure 27: Installation of thermistor string at monitoring Station 2

Figure 28: Data logging instrumentation installed at monitoring Station 1

Figure 29: Installation and programming of data logging equipment

Table 1: Instrumentation layout at monitoring station 1 on Eielson AFB, AK.

Depth (m)	Depth (ft)	Sensor Cable Length (m)	Sensor Information	Offset From 0°C
Ambient	Ambient	2	Temp, °C (LGR S/N: 20168199, SEN S/N: 20171362)	2.685
0.1524	0.5	2	Temp, °C (LGR S/N: 20168199, SEN S/N: 20160656)	-0.131
0.3048	1	2	Temp, °C (LGR S/N: 20168199, SEN S/N: 20160657)	0.024
0.4572	1.5	2	Temp, °C (LGR S/N: 20168199, SEN S/N: 20160655)	0.002
0.6096	2	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20182672)	0.108
0.762	2.5	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20168341)	-0.025
0.9144	3	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20168340)	0.081
1.0668	3.5	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20168339)	0.001
1.2192	4	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20168342)	-0.059
1.524	5	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20168343)	0.037
2.286	7.5	17	Temp, °C (LGR S/N: 20168199, SEN S/N: 20166912)	0.148
3.048	10	17	Temp, °C (LGR S/N: 20168199, SEN S/N: 20166913)	0.187

Table 2: Instrumentation layout at monitoring station 2 on Eielson AFB, AK.

Depth (m)	Depth (ft)	Sensor Cable Length (m)	Sensor Information	Offset From 0°C
0.152	0.5	2	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177167)	-0.102
0.305	1	2	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177163)	0.024
0.457	1.5	2	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177166)	0.024
0.610	2	2	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177165)	0.081
0.762	2.5	2	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177164)	0.024
1.067	3.5	6	Temp, °C (LGR S/N: 20177931, SEN S/N: 20182674)	-0.004
1.372	4.5	6	Temp, °C (LGR S/N: 20177931, SEN S/N: 20182671)	0.079
1.524	5	6	Temp, °C (LGR S/N: 20177931, SEN S/N: 20182673)	0.104
3.048	10	17	Temp, °C (LGR S/N: 20177931, SEN S/N: 20166925)	0.135

IV. Results and Analysis

Results of Calibration Test

A distilled water ice slurry provided stable platform for a true 0ºC environment, as depicted in Figure 30. The calibration test was derived from the methods used by researchers at the UAF Permafrost Laboratory, and posted in video form on their website. The sensors were immersed in the slurry at approximately 1 inch spacing. The slurry was monitored for melt water buildup. The test vessel was drained of meltwater at 5 minute intervals throughout each of the calibration tests. Tap water ice was used as an insulator to slow the melting process. All sensors were allowed to cool for 30 minutes. Data collected during this period is depicted in the following figure, and the following table summarizes the offset calibration values for each sensor. The maximum temperature offset observed for underground sensors was 0.187ºC, and the smallest offset was 0.0009112ºC. The ambient temperature sensor indicated an offset of 2.685ºC. The ambient humidity sensor was not calibrated prior to deployment due to lack of appropriate facilities in which to conduct the test.

Figure 30: Calibration Test Setup

Results of Site Selection

Four sites had been initially chosen for the station installations. Geospatial information (GIS) products were used to visually select possible sites based on several criteria. The station had to be located outside of the active airfield, in order to reduce the impact on base operations, and to avoid a lengthy permitting/licensing process. The station must also be located in an area where an effective GPR and ERT survey could be completed. Since the stations would be installed in late July, the transect lines would need to be relatively flat, with no significant obstacles or undulations that would affect the success of the surveys. The absence of standing water was also desired, in order to ensure the effectiveness of the survey equipment and accessibility of the drill rig.

Site 1 Summary

Site 1 included a combination of Black Spruce and mixed ground cover. Aerial imagery of the site indicated that there may be a straight line pathway already cleared on the site. Site visits during the field work proved that this trail was intact, but would require days of ground clearing prior to survey, due to significant standing dead and fallen dead trees, as well as overgrown heavy brush, as shown in Figure 31.

Figure 31: Site 1

Site 2 Summary

Site 2, shown in Figure 32, was initially selected from GIS imagery due to the appearance of a substantially cleared area near where a possible transect could be surveyed. Upon physical inspection, the site was found to be largely swamp land, with tussock and standing water.

Figure 32: Site 2

Site 3 Summary

Site 3 was an extension of the same drainage body found at Site 2, pictured in Figure 33. For the same reasons, Site 3 was not a good candidate for installing the ground stations.

Figure 33: Site 3

Site 4 Summary

Site 4 was initially selected as a candidate because it appeared to be a previously cleared trail, with a straight line appearance and an absence of trees. Site 4 is pictured in Figure 34. As was true at Site 1, the trail was much more overgrown than initially believed. The site would have required deadfall removal, and brush clearing.

Figure 34: Site 4

“Site 5” Summary

The research team scouted the area nearer the South Loop taxiway in an effort to find a more suitable site for ground station installation. After investigating the area North and West of Site 4, the team found an area near a natural slough adjacent to the South Loop. The site is depicted in Figure 35 as Site 5. This transect offered an undisturbed stand of trees with little brush, a natural water feature, and a previously disturbed area. These features made Site 5 the most interesting for additional investigation. Due to the uneven terrain this area, the GPR survey was not conducted. Uneven terrain was primarily caused by the existence of a slough and an abandoned perimeter fence/berm. Instead, an ERT was conducted along two intersecting transects in order to target the best area for monitoring.

Figure 35: Site 5, Final Site Selected

ERT Survey

The ERT survey indicated that an area within 500 m of the South Loop construction area was likely to contain permafrost. Station 1 would be installed at this location, where a thaw susceptible bulb of permafrost ground may be present, and where slough inflow had caused thawing already, as depicted in Figure 36. Tree cover was limited to sporadic spruce.

The ERT survey also indicated that a control location could be located further east from the South Loop, and exhibited resistivity that was indicative of more stable and continuous permafrost. The ground cover included older growth (larger) spruce and birch trees, as well as low grass and ferns. The organic layer in this area was much less compact than at Station 1, with abundant feather mosses.

The permafrost at Station 1 appeared to be located within 3m from the surface of the ground. The permafrost layer appeared to extend to a depth of approximately 5m beneath the ground surface. A frost probe of the area indicated the bottom of the active layer on the day of station installation was 0.41m below the surface at Station 1 and 0.52m at Station 2. The active layer would continue to thaw for a few more weeks Eielson AFB's latitude, but was a good general indicator of the top of the permafrost layer.

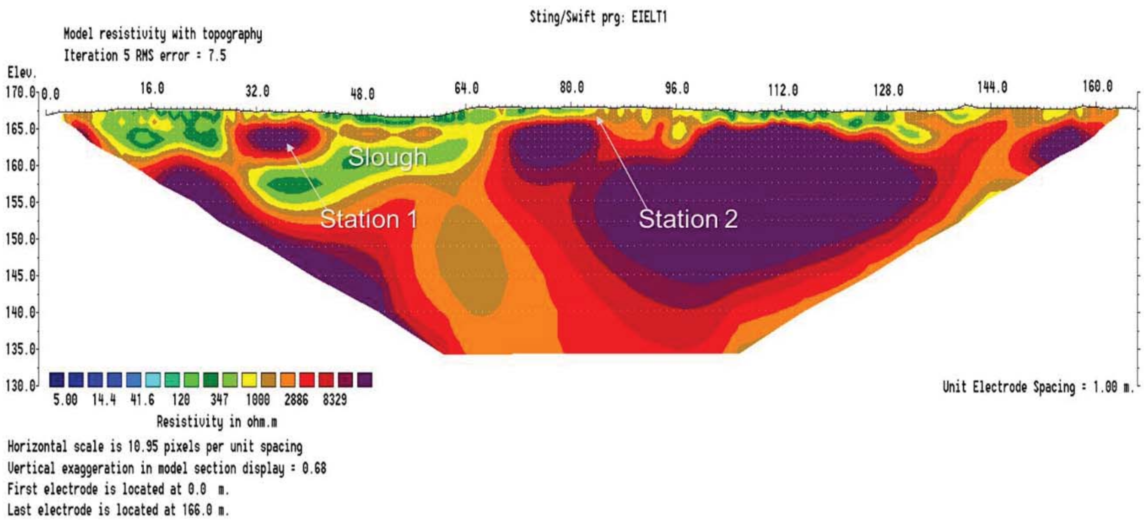


Figure 36: Transect 1 ERT Results

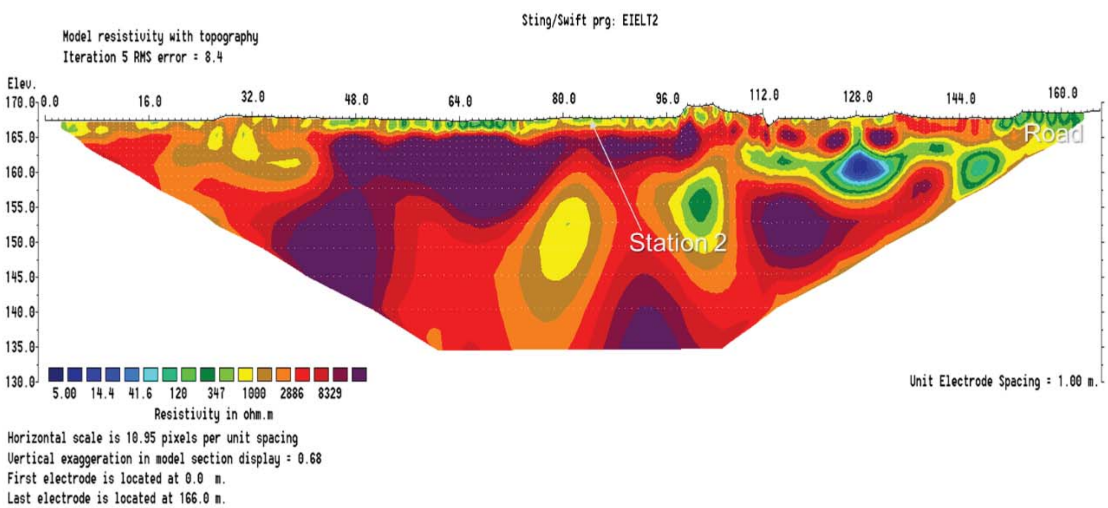


Figure 37: Transect 2 ERT Results

Drilling

The first step to install the monitoring stations was to bore a hole through the soil to our desired depth. The drill rig was able to easily accomplish this task, with soil samples documented as each 4ft section was drilled. Push drilling was implemented for both station locations using a 2in diameter probe. The only anomaly encountered during the drilling process was a stuck sample sleeve during the drilling at Station 2, which prevented a complete soil analysis for the boring at that site. Soil analysis for Station 1 concluded with no incidents. In general, the soil at Station 1 was a mix of alternating gravel and silt layers, with an organic layer of 9-in above the first layer of silt. The drill and soil sample are depicted in Figure 38, Figure 39, and Figure 40.

Figure 38: Drilling Rig with Casing Installed

Figure 39: Pulling Acrylic Sleeves from Dill for Analysis

Figure 40: First Soil Sample from Station 2

Table 3: Soil Moisture Results

Sample Depth (m)	Tare (Wc) (g)	Starting Total Mass (W1) (g)	Ending Total Mass (W2) (g)	Ending Soil Mass (Ws=W2-Wc) (g)	Water Mass (Ww=W1-W2) (g)	Water Content (WC= 100*(Ww/Ws)) (% water)
0.406	22.300	131.700	105.300	83.000	26.400	31.81%
0.660	19.200	189.000	148.600	129.400	40.400	31.22%
1.118	19.100	235.200	198.300	179.200	36.900	20.59%
1.448	21.600	231.000	205.900	184.300	25.100	13.62%
1.905	21.300	313.100	289.300	268.000	23.800	8.88%
2.261	21.500	266.900	201.000	179.500	65.900	36.71%
2.413	20.900	240.200	225.800	204.900	14.400	7.03%
2.540	21.400	220.800	204.000	182.600	16.800	9.20%
2.921	21.600	246.700	238.300	216.700	8.400	3.88%

Various soil samples representing each strata were collected during the drilling process and later analyzed for moisture content. The soil was very moist during drilling, with some showing liquid water and some frozen solid. A summary of the soil moisture samples is included in Table 3 (TxDOT, 1999).

While some frozen ground was apparent during drilling, soil samples were not directly measured for temperature. Therefore, it is difficult to claim the existence of any particular ground temperature during the drilling process. The drill probe imparts an amount of energy into the ground during drilling, so some soil warming likely occurred immediately before the soil was extracted from the acrylic sleeve. The results of the frost probe survey are shown in Figure 41 and Figure 42. The frost probe survey indicated that frozen ground did exist within the 10 ft drilling depth in several locations. A complete soil boring log and photos of all soil samples are included in the Appendix.

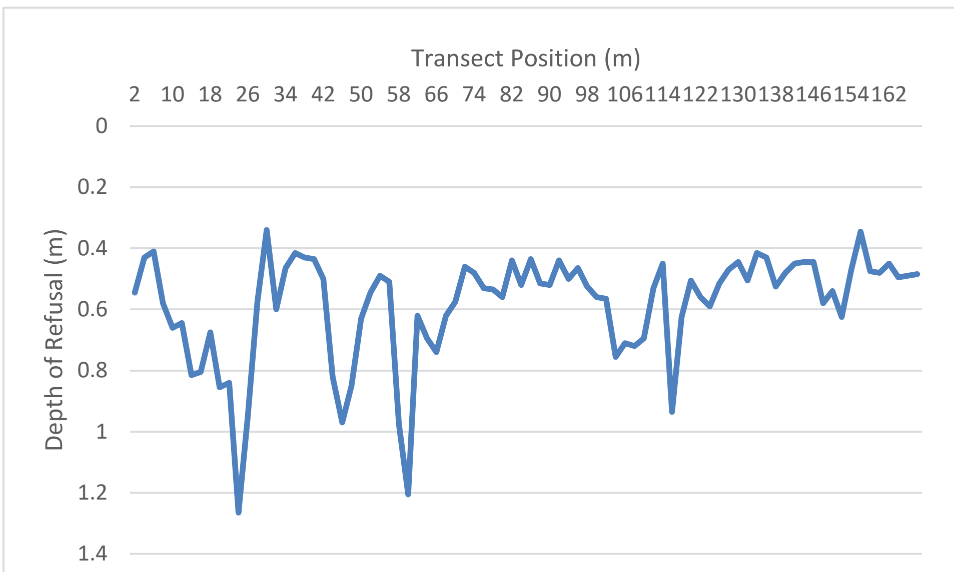


Figure 41: Frost Probe Results Transect 1 (EIELT1)

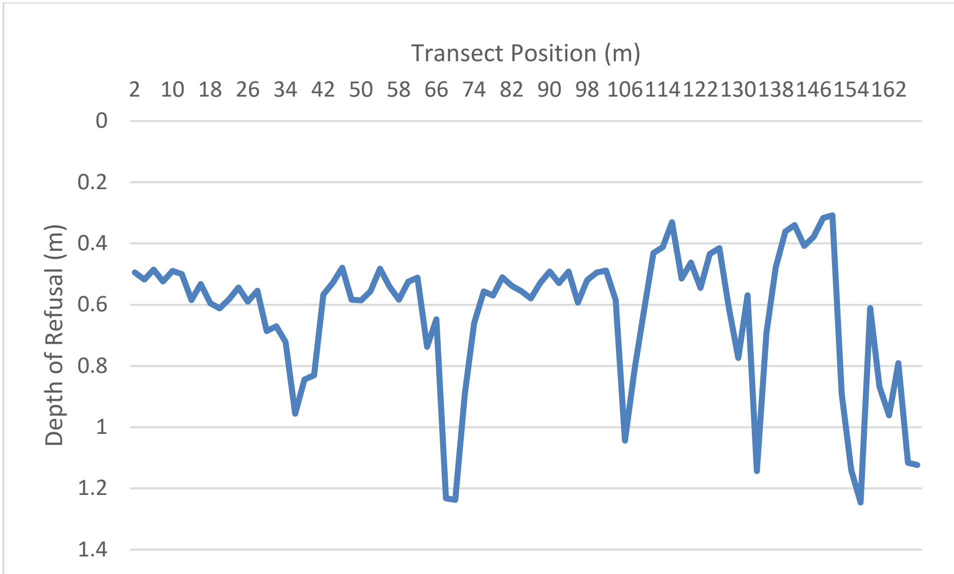


Figure 42: Frost Probe Results Transect 2 (EIELT2)

Temperature Monitoring

The stations were installed at each site as described in Chapter 3 of this document, and successfully recorded temperature at 1 hour intervals for 55 consecutive days between 27 July and 20 Sept 2017. One researcher returned to the site on 20 Sept 2017 in order to pull data from the loggers and inspect the condition of the stations. Both stations were intact and operating as expected. No disturbance of the thermistor probes occurred and the settings on the loggers remained unchanged. The loggers will continue to function throughout the winter of 2017/2018 until data can be pulled again and periodic maintenance performed. Data collected during this visit was aggregated and analyzed.

The ground temperatures at Station 1 were adjusted for calibration offsets and indicate that there is likely frozen ground at the site, but at a depth greater than where the instrumentation was installed. After settling for several days, the steady state temperatures at Station 1 varied from about 7°C at half meter depth to just a few tenths of a degree above freezing at the bottom of the 3 meter casing. The top half meter varied in temperature greatly due to daily ambient weather conditions, and never reached a steady reading for more than one hour. The following table shows temperature and depth during 5 hours of sampling; a complete data set can be seen in the Appendix.

Table 4: Sample Data from Station 1

Sensor Depth (ft)	Ambient	0.5	1
Sensor Depth (m)	Ambient	0.1524	0.3048
Calibration Offset (°C)	2.684959064	-0.131315789	0.024
Date Time, GMT-04:00	Temp, °C (LGR S/N: 20168199, SEN S/N: 20171362)	Temp, °C (LGR S/N: 20168199, SEN S/N: 20160656)	Temp, °C (LGR S/N: 20168199, SEN S/N: 20160657)
7/27/2017 14:09	15.41194152	16.29394152	14.02394152
7/27/2017 15:09	20.43394152	23.01394152	16.50894152
7/27/2017 16:09	21.57894152	23.27794152	18.05494152
7/27/2017 17:09	25.03794152	24.33694152	18.79194152

Table 5: Sample Data from Station 2

Depth (ft)>	0.5	1	1.5
Depth (m)>	0.1524	0.3048	0.4572
Offset (°C)>	-0.102245614	0.024	0.024
Date Time, GMT-04:00	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177167)	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177163)	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177166)
7/27/2017 14:30	8.596245614	4.274	2.104
7/27/2017 15:30	9.142245614	4.352	2.104
7/27/2017 16:30	10.34924561	4.534	2.131
7/27/2017 17:30	12.15224561	4.845	2.185

Permafrost exists within 3 meters of the ground surface at Station 2. Frozen ground is continuously observed at both the 2m and 3m depths, with frozen ground likely occurring continuously between. The frozen ground ranges in temperature from about -0.080ºC to -0.028ºC. The following table shows temperature and depth during three days of sampling; a complete data set can be seen in the Appendix.

Station 1 included an ambient temperature and humidity probe in addition to the ground temperature probes. The data logger collected the respective measurements at the same time intervals as the ground temperatures. Because this data could be easily compared to other nearby weather stations, and because high and low temperature points in the Tanana Valley is not usually widely variable in the summer months, the collected data was compared to four other stations. The National Weather Service weather stations at Fairbanks International Airport, North Pole, Manchu, and Aurora were used for comparison.

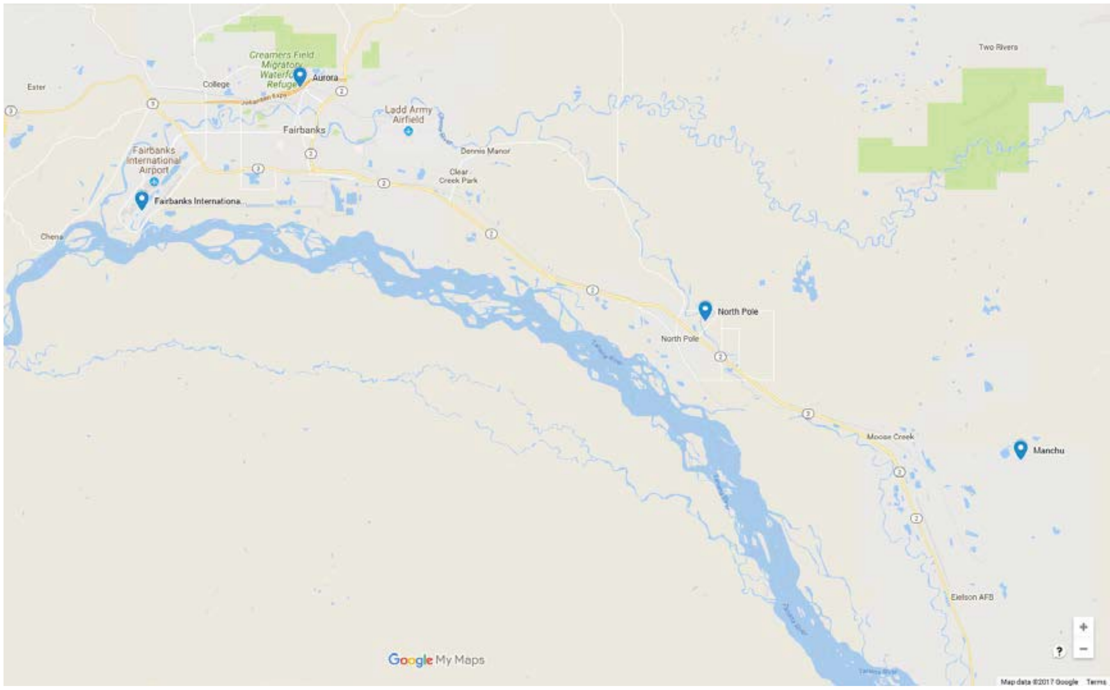


Figure 43: Weather Stations Used for Statistical Comparison

The data was processed for high and low temperature during each day, considered 0000-2359 Alaska Standard Time (AKST), and then compared statistically to the high and low temperatures from the other stations. The statistical analysis included a two sample t-test for each NWS station vs. data from Station 1, the results of which are shown in Table 6. National Weather Service stations were also compared to one another, to establish whether or not those stations experienced unique temperature and humidity condition from one another.

Table 6: Temperature Data Statistical Comparison

	Variable 1	*North Pole High*
Mean	18.8387597	18.92181818
Variance	34.4896943	21.71247811
Observations	55	55
Pooled Variance	28.10108621	
Hypothesized Mean Difference	0	
df	108	
t Stat	-0.082165361	
P(T<=t) one-tail	0.467333652	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.934667304	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Manchu High*
Mean	18.8387597	19.23090909
Variance	34.4896943	22.15513805
Observations	55	55
Pooled Variance	28.32241617	
Hypothesized Mean Difference	0	
df	108	
t Stat	-0.386413899	
P(T<=t) one-tail	0.3499752	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.6999504	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Aurora High*
Mean	18.8387597	18.22545455
Variance	34.4896943	17.92934007
Observations	55	55
Pooled Variance	26.20951718	
Hypothesized Mean Difference	0	
df	108	
t Stat	0.628222451	
P(T<=t) one-tail	0.265592242	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.531184483	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Fairbanks High*
Mean	18.8387597	18.57818182
Variance	34.4896943	20.07988552
Observations	55	55
Pooled Variance	27.28478991	
Hypothesized Mean Difference	0	
df	108	
t Stat	0.261603526	
P(T<=t) one-tail	0.397062691	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.794125382	
t Critical two-tail	1.982173483	

	Variable 1	*North Pole Low*
Mean	4.840905157	8.190909091
Variance	18.86910007	16.99861953
Observations	55	55
Pooled Variance	17.9338598	
Hypothesized Mean Difference	0	
df	108	
t Stat	-4.148344152	
P(T<=t) one-tail	3.34762E-05	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	6.69523E-05	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Manchu Low*
Mean	5.256363636	6.565454545
Variance	19.79954209	15.16563636
Observations	55	55
Pooled Variance	17.48258923	
Hypothesized Mean Difference	0	
df	108	
t Stat	-1.641849243	
P(T<=t) one-tail	0.051765051	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.103530103	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Aurora Low*
Mean	5.256363636	7.472727273
Variance	19.79954209	17.98609428
Observations	55	55
Pooled Variance	18.89281818	
Hypothesized Mean Difference	0	
df	108	
t Stat	-2.673985146	
P(T<=t) one-tail	0.00432996	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.008659919	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances

	Station 1 Min	*Fairbanks Low*
Mean	5.256363636	8.190909091
Variance	19.79954209	16.99861953
Observations	55	55
Pooled Variance	18.39908081	
Hypothesized Mean Difference	0	
df	108	
t Stat	-3.587642205	
P(T<=t) one-tail	0.000251498	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.000502996	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	FAI Low Temp	*North Pole Low*
Mean	8.190909091	5.256363636
Variance	16.99861953	19.79954209
Observations	55	55
Pooled Variance	18.39908081	
Hypothesized Mean Difference	0	
df	108	
t Stat	3.587642205	
P(T<=t) one-tail	0.000251498	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.000502996	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	FAI High	*North Pole High*
Mean	18.57818182	18.92181818
Variance	20.07988552	21.71247811
Observations	55	55
Pooled Variance	20.89618182	
Hypothesized Mean Difference	0	
df	108	
t Stat	-0.394213953	
P(T<=t) one-tail	0.347100203	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.694200406	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	FAI Low	*Aurora Low*
Mean	8.190909091	7.472727273
Variance	16.99861953	17.98609428
Observations	55	55
Pooled Variance	17.4923569	
Hypothesized Mean Difference	0	
df	108	
t Stat	0.900485218	
P(T<=t) one-tail	0.184932838	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.369865676	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	FAI High	*Aurora High*
Mean	18.57818182	18.22545455
Variance	20.07988552	17.92934007
Observations	55	55
Pooled Variance	19.00461279	
Hypothesized Mean Difference	0	
df	108	
t Stat	0.424302777	
P(T<=t) one-tail	0.336094508	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.672189016	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	FAI Low	*Manchu Low*
Mean	8.190909091	6.565454545
Variance	16.99861953	15.16563636
Observations	55	55
Pooled Variance	16.08212795	
Hypothesized Mean Difference	0	
df	108	
t Stat	2.125540673	
P(T<=t) one-tail	0.017910485	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.03582097	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	FAI High	*Manchu High*
Mean	18.57818182	19.23090909
Variance	20.07988552	22.15513805
Observations	55	55
Pooled Variance	21.11751178	
Hypothesized Mean Difference	0	
df	108	
t Stat	-0.744863569	
P(T<=t) one-tail	0.228986014	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.457972029	
t Critical two-tail	1.982173483	

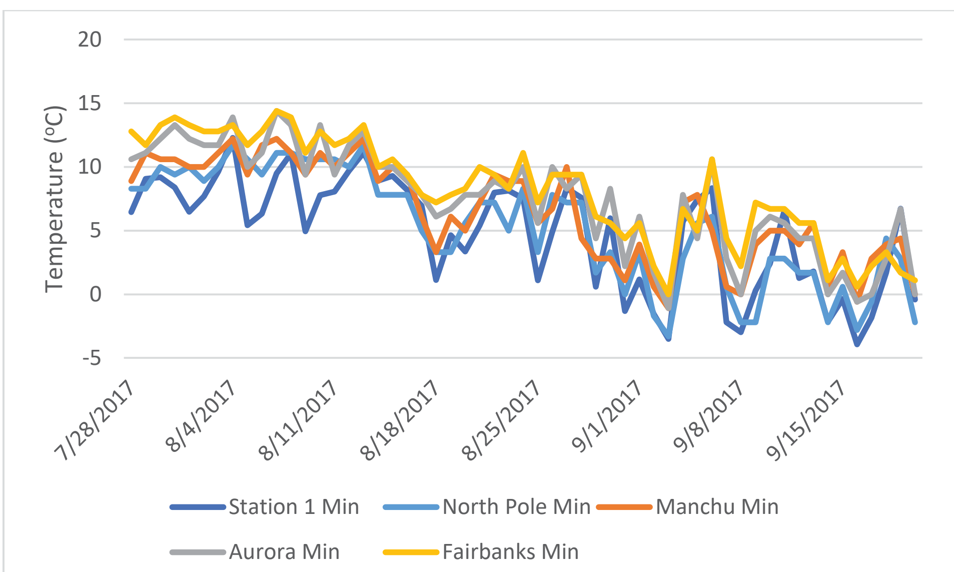


Figure 44: Daily Low Temperature Data

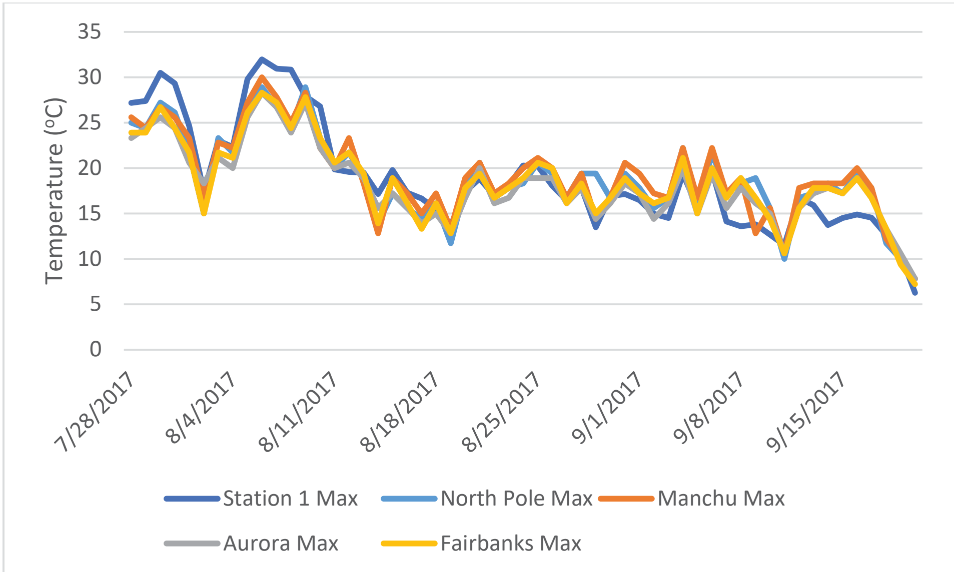


Figure 45: Daily High Temperature Data

Station 1 was statistically similar to all stations for the daily high temperature, although it was not possible to establish a trend where Station 1 consistently recorded temperatures that were above or below the other stations. Figure 44 and Figure 45 show the temperature trends across time. Station 1 was statistically similar only to the Manchu station for daily low temperature. The Manchu station is the closest NWS station, and most similar in geographic elevation and ground cover to that of Station 1. Further data analysis will be required in the future to continue trend analysis of the ambient temperature instrumentation at Station 1. When comparing NWS data sets against one another, it was a mixed outcome for daily low temperature, with FAI only being similar to Aurora. For daily high temperature, statistically each station is unique.

Station 1 also included an ambient humidity sensor, the data from which is depicted in Figure 46 and Figure 47. High and low daily humidity values were analyzed statistically in the same manner as the high and low temperature, and the statistical results can be seen in Table 7. The humidity data for comparison was supplied by the Geographic Information Network of Alaska. The statistical analysis indicates that the humidity data being gathered at Station 1 is not statistically similar to the other stations, as the data is almost universally higher than the daily values being recorded by nearby weather stations, and fails the hypothesis test with P=0.05. The high humidity readings at Station 1 don't seem to correlate to days with measurable precipitation. The sensor location near to the ground may be causing the high readings in some cases, but the instrumentation was also not calibrated prior to deployment, so it is difficult to know if an offset exists from true "0%" and "100%" humidity readings. When comparing the FAI and Manchu humidity data sets to one another, the results indicate that these two data sets are also statistically different.

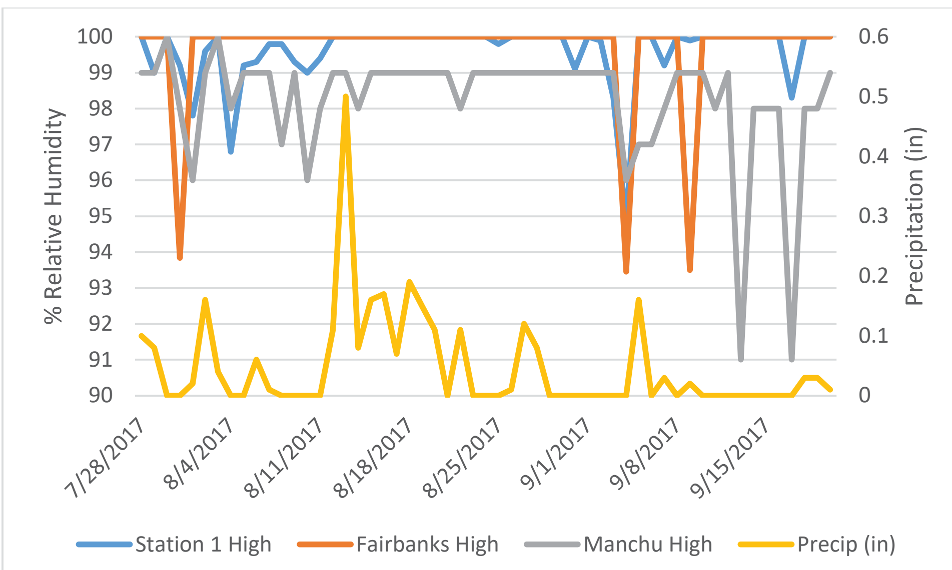


Figure 46: Daily High Humidity and Precipitation Data

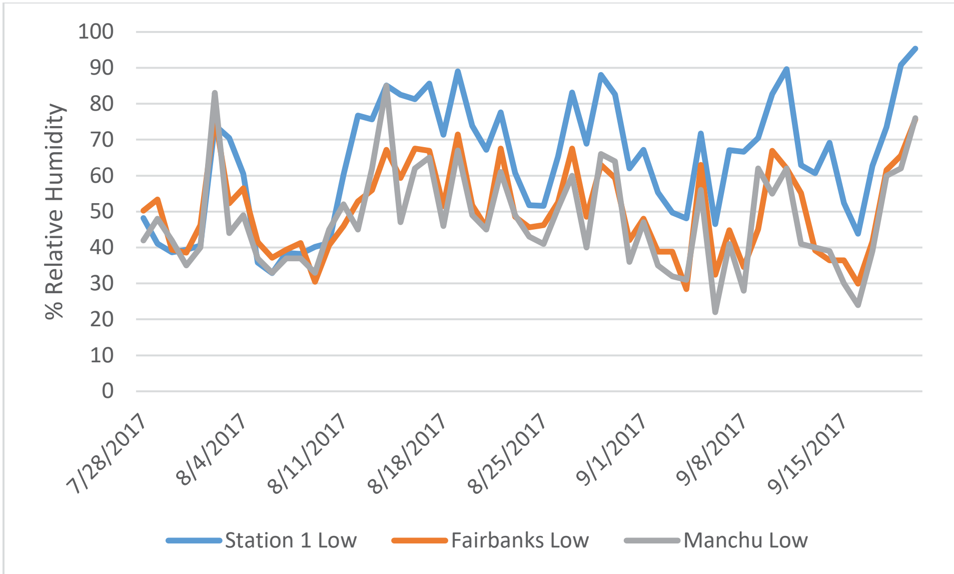


Figure 47: Daily Low Humidity Data

Table 7: Humidity Data Statistical Comparison

t-Test: Two-Sample Assuming Equal Variances		
	Station1	*FAI High*
Mean	99.59090909	99.65072727
Variance	0.834545455	2.155343906
Observations	55	55
Pooled Variance	1.49494468	
Hypothesized Mean Difference	0	
df	108	
t Stat	-0.256558847	
P(T<=t) one-tail	0.399003719	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	0.798007439	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	Station 1	*FAI Low*
Mean	63.74727273	50.27581818
Variance	290.6677239	154.651184
Observations	55	55
Pooled Variance	222.659454	
Hypothesized Mean Difference	0	
df	108	
t Stat	4.734348974	
P(T<=t) one-tail	3.35462E-06	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	6.70924E-06	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	Station 1	*Manchu High*
Mean	99.59090909	98.25454545
Variance	0.834545455	2.785858586
Observations	55	55
Pooled Variance	1.81020202	
Hypothesized Mean Difference	0	
df	108	
t Stat	5.208677564	
P(T<=t) one-tail	4.58727E-07	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	9.17453E-07	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	Station 1	*Manchu Low*
Mean	63.74727273	47.69090909
Variance	290.6677239	197.1063973
Observations	55	55
Pooled Variance	243.8870606	
Hypothesized Mean Difference	0	
df	108	
t Stat	5.391618595	
P(T<=t) one-tail	2.07204E-07	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	4.14408E-07	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	FAI RH High	*Manchu RH High*
Mean	99.65072727	98.25454545
Variance	2.155343906	2.785858586
Observations	55	55
Pooled Variance	2.470601246	
Hypothesized Mean Difference	0	
df	108	
t Stat	4.658080579	
P(T<=t) one-tail	4.57247E-06	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	9.14494E-06	
t Critical two-tail	1.982173483	

t-Test: Two-Sample Assuming Equal Variances		
	FAI RH Low	*Manchu RH Low*
Mean	47.69090909	98.25454545
Variance	197.1063973	2.785858586
Observations	55	55
Pooled Variance	99.94612795	
Hypothesized Mean Difference	0	
df	108	
t Stat	-26.5229398	
P(T<=t) one-tail	2.07911E-49	
t Critical one-tail	1.659085144	
P(T<=t) two-tail	4.15822E-49	
t Critical two-tail	1.982173483	

Lastly, the monitoring stations collected ground temperature data, and continue to do so. The ground temperature data was statistically compared to three other stations in the Fairbanks area over a period of 8/1/2018 – 9/20/2018. Each station's data was summarized as the average temperature of permafrost, using only those temperature data points from the permafrost layer in each borehole. The temperature/depth data that was in the active layer was not used for statistical comparison. The non-Eielson stations are all operated by the UAF Permafrost Lab, and are of similar depth, soil composition, and ground cover as the stations at Eielson. Summarily, the Eielson data was too dissimilar from the UAF stations to make any correlation. The Eielson data, when compared using a two tailed t-test with a 95% confidence interval, was not similar to the UAF data over the given time period. The results of the statistical comparison are included in Table 8.

While this indication of non-similarity seems straightforward, there are many variables at work that are pulling the datasets in different directions. All of the stations differ in the number and location of thermistors. The depths of the thermistors and the separation of thermistors varied between all of the stations. So, averages of permafrost temperature were used to give a representative temperature for the permafrost at each location.

Table 8: Ground Temperature Statistical Comparison

t-Test: Two-Sample Assuming Equal Variances

	Eielson Station 1	*Fox*
Mean	0.137882697	-0.116124183
Variance	0.001792804	0.002383186
Observations	51	51
Pooled Variance	0.002087995	
Hypothesized Mean Difference	0	
df	100	
t Stat	28.07054333	
P(T<=t) one-tail	1.60573E-49	
t Critical one-tail	1.660234326	
P(T<=t) two-tail	3.21146E-49	
t Critical two-tail	1.983971519	

t-Test: Two-Sample Assuming Equal Variances

	Eielson Station 2	*Fox*
Mean	-0.098626656	-0.116124183
Variance	0.000161883	0.002383186
Observations	51	51
Pooled Variance	0.001272535	
Hypothesized Mean Difference	0	
df	100	
t Stat	2.476919971	
P(T<=t) one-tail	0.007464853	
t Critical one-tail	1.660234326	
P(T<=t) two-tail	0.014929706	
t Critical two-tail	1.983971519	

t-Test: Two-Sample Assuming Equal Variances

	Eielson Station 1	*Smith Lake 1*
Mean	0.137882697	-0.274794118
Variance	0.001792804	0.000202762
Observations	51	51
Pooled Variance	0.000997783	
Hypothesized Mean Difference	0	
df	100	
t Stat	65.97237797	
P(T<=t) one-tail	1.49683E-84	
t Critical one-tail	1.660234326	
P(T<=t) two-tail	2.99366E-84	
t Critical two-tail	1.983971519	

t-Test: Two-Sample Assuming Equal Variances

	Eielson Station 2	*Smith Lake 1*
Mean	-0.098626656	-0.274794118
Variance	0.000161883	0.000202762
Observations	51	51
Pooled Variance	0.000182322	
Hypothesized Mean Difference	0	
df	100	
t Stat	65.88340886	
P(T<=t) one-tail	1.70795E-84	
t Critical one-tail	1.660234326	
P(T<=t) two-tail	3.41589E-84	
t Critical two-tail	1.983971519	

t-Test: Two-Sample Assuming Equal Variances

	Eielson Station 1	*Smith Lake 3*
Mean	0.137882697	-0.188529412
Variance	0.001792804	0.002768134
Observations	51	51
Pooled Variance	0.002280469	
Hypothesized Mean Difference	0	
df	100	
t Stat	34.51630204	
P(T<=t) one-tail	1.15971E-57	
t Critical one-tail	1.660234326	
P(T<=t) two-tail	2.31942E-57	
t Critical two-tail	1.983971519	

t-Test: Two-Sample Assuming Equal Variances

	Eielson Station 2	*Smith Lake 3*
Mean	-0.098626656	-0.188529412
Variance	0.000161883	0.002768134
Observations	51	51
Pooled Variance	0.001465008	
Hypothesized Mean Difference	0	
df	100	
t Stat	11.86104754	
P(T<=t) one-tail	4.3757E-21	
t Critical one-tail	1.660234326	
P(T<=t) two-tail	8.75139E-21	
t Critical two-tail	1.983971519	

Investigative Questions Answered

What is the depth and extent of permafrost on Eielson AFB, and what are the characteristics of the soils? The depth and extent of permafrost on Eielson AFB varies widely depending on specific location. During this investigation, discontinuous permafrost existed in the entire area of the ERT survey, from depths of 3m-25m, with the individual permafrost features varying widely in thickness.

How should the apparent existing degradation impact plans for future base expansion and land use? The Air Force and the DoD should continue to refine their strategies for operations in the Arctic. Research accomplished by others in government and academia suggests that changing hydrology in areas where permafrost exist may create accelerated degradation. As permafrost melts, the groundwater movement around the permafrost also increases, and small precipitation events can cause rapid degradation as water moves through areas where drainage occurs.

Summary

Although the data set collected is only a portion of the larger and more relevant annual ground temperature profile that includes seasonal effects, the data collected during the first month and half of operation is important. The data indicates that the ground temperature instrumentation is working correctly, and gives important clues to how this field experiment can be improved during the next summer season in order to gather higher quality data.

V. Conclusions and Recommendations

Permafrost soil is susceptible to considerable thaw due to anthropogenic activity. Although the process occurs worldwide at a rate in the scale of tenths of degrees per year, the potential change in geotechnical composition and strength are considerable. The permafrost at Eielson AFB is nearly thawed at the depths investigated in this experiment. Further data collection and analysis should be conducted in order to develop degradation rate information, as well as to quantify the rate of additional energy input into the ground through hydrology changes from the F-35 construction program.

Conclusions of Research

Permafrost is near the thaw point at Eielson AFB. The level of discontinuity in the vertical dimension indicates that the existing permafrost is very sporadic in nature, susceptible to additional thawing if additional energy is input into the ground. As mentioned before, this ground is unlikely to experience significant differential settlement due to lack of existing facilities using virgin ground. Many of the new F-35 facilities utilized over-excavation of the natural soils, and the introduction of compacted, engineered fill material to combat thaw settlement. From an environmental perspective, the existing permafrost should be preserved to the greatest extent possible using passive and active strategies. Stewardship of permafrost is key, just like strategies used to preserve waterways, forests, and other natural resources. In those locations where ground cover remains undisturbed, it should remain that way on purpose. Existing airfield pavements should not expand into permafrost locations, but rather utilize areas which have been previously disturbed and thawed. Active stewardship of the existing permafrost will prevent the organic material within the soil from rapidly degrading and adding to the already out of balance carbon cycle in the arctic.

Many factors could provide the tipping point that completes the thawing of permafrost near the South Loop at Eielson AFB. The most significant local anthropogenic factor appears to be the construction of new facilities and airfield pavements, which include new storm water management schemes. The energy input into the ground from storm water runoff should be further analyzed and compared to the potential impacts from future IPCC climate scenarios. Hydrology will likely play a larger role in thawing the existing permafrost than the warming climate.

The temperature profile gathered from Station 2 indicate that there is a noticeable temperature shift between the five and ten foot depths. To better understand the ground temperature profile, more monitoring points should be installed at the existing casing. At Station 1, a deeper boring should be accomplished in order to discover the true depth of the existing permafrost, if any, at that location. Initial data shows ground that is within 0.13°C of freezing during the warmest months, and that is seasonally frozen around the middle of September at the bottom of the existing casing. To better understand where the existing permafrost table lies, the follow on research team should conduct additional ERT surveys in order to continue building a sight picture of the state of frozen ground in the vicinity of the monitoring stations.

Weather data gathered at the experiment site has limited use. Due to the inaccuracy of the ambient humidity data, it should not be used for any scientific purpose. A higher quality weather station should be installed at Station 1 to ensure valid and useful weather data. The temperature data set is statistically valid, and may be used for site specific analysis of climate regimes in the local area around Station 1.

Significance of Research

The establishment of the two ground monitoring stations at Eielson AFB are the first long term permafrost monitoring sites owned by the Air Force specifically targeting anthropogenic effects to permafrost degradation. The collection of multi-year ground temperature data will give Air Force and DoD engineers and planners site specific knowledge of the effects of major development on existing warm discontinuous permafrost. This site specific knowledge can be correlated to other areas with similar permafrost conditions, and will aid in decision making and planning for continued sustainable operations in the Arctic.

Recommendations for Action

The Air Force and DoD should continue to monitor permafrost conditions at Eielson AFB in the future in order to establish a good baseline for the permafrost degradation rates in this area. With a $550M portfolio of new construction and major renovation, the small investment in permafrost knowledge will aid engineers in the future to understand how the soil bearing capacity is changing in this area. The permafrost on DoD installations in the Arctic should also be actively stewarded in order to minimize the DoD's impact on carbon emissions from thawing permafrost. Shortly after permafrost thaws, carbon release begins in the form of decaying organics and the release of trapped carbon from the ground in the form of GHGs. This carbon release further accelerates the carbon cycle that is largely responsible for permafrost melting in the Arctic in the first place. For this reason, the DoD should actively steward the permafrost that remains on its installations as it develops strategies for future operations. The most important factor in this effort is the consideration of existing permafrost soils when base development plans and future facility construction plans are being developed. Areas where permafrost exists should be off-limits to new anthropogenic activity whenever mission requirements allow. Simple strategies could include limiting new construction to areas that have previously experienced development, or where no permafrost exists. More complex strategies may include re-vegetating forest land, ensuring impervious surfaces drain to non-permafrost areas, and zoning permafrost areas as off-limits to future land use.

Recommendations for Future Research

The Air Force and DoD engineering communities should continue long term monitoring of permafrost soils in areas where significant construction activities are occurring or are planned to occur – especially where changes in runoff/hydrology are likely. Today, very little data has been gathered on DoD installations. Data collection should begin now, preemptively, in order to ensure that planning and design happens according to recent and site-specific trends. A second priority should be the complete review and validation of all UFC design guides dealing with permafrost soils and construction methods. Due to the age of the data used to build the majority of the cold regions design guides, it is important to periodically update and refine the data that guides our execution of infrastructure and facility design.

From the perspective of the Eielson ground stations, there should be an increase in the number of thermistors in active layer and frozen ground regimes in order to enhance the resolution of the dataset and ensure that data is being collected where permafrost really exists, as well as a deepening overall borehole to ensure the permafrost table depth is well within the reach of the thermistor strings.

All of the future goals of this project can be reached through the leveraging of strategic partnerships with USACE CRREL and GTN-P researchers. Many of the relevant data collection methods and engineering solutions for Arctic construction have been studied by others. If this project will continue to be of high value, it should align with the practices and lessons learned from academia and industry, as well as being centered on specific DoD mission beddowns and future operations strategies.

Appendix A: Supplemental Soil Sample Photos


2 3 4 5 6 7 8 9 10 11 1F 12 13 14


6 7 8 9 10 11 1F 12 13 14 15 16 17 18


16 17 18 19 20 21 22 23
2F 24
25 26


2F 24
25 26 27 28 29 30 31 32 33 34


33 34 35 3F 36 37 38 39 40 41 42


40 41 42 43 44 45 46 47 4F 48 49


47
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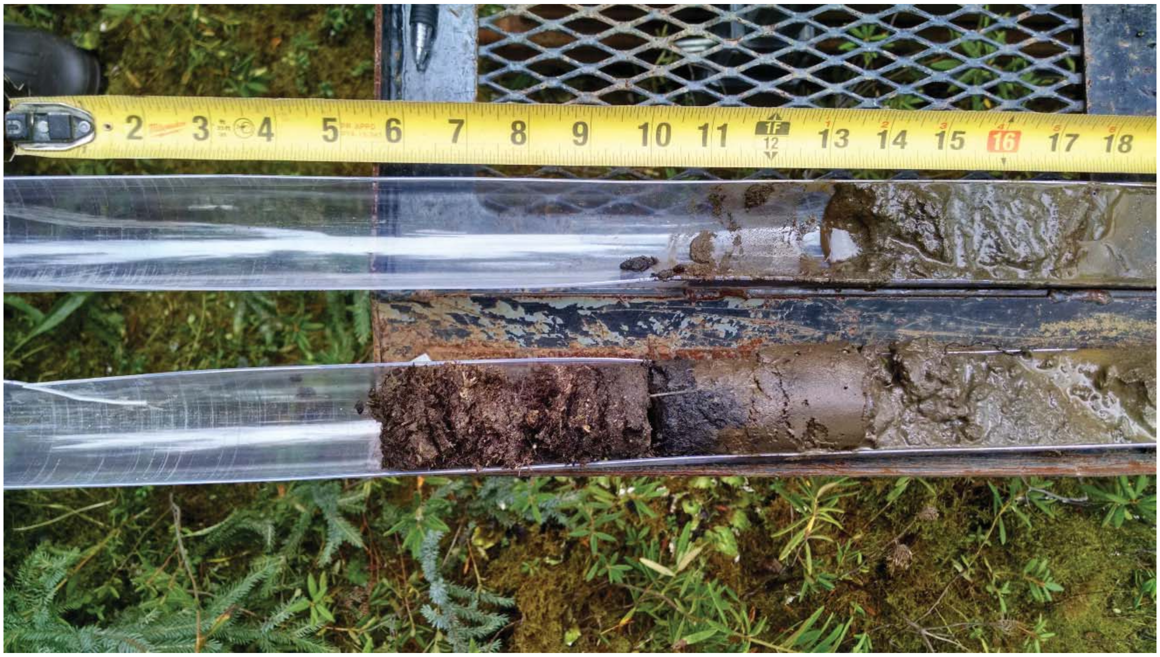
Station 2 Soil Samples:

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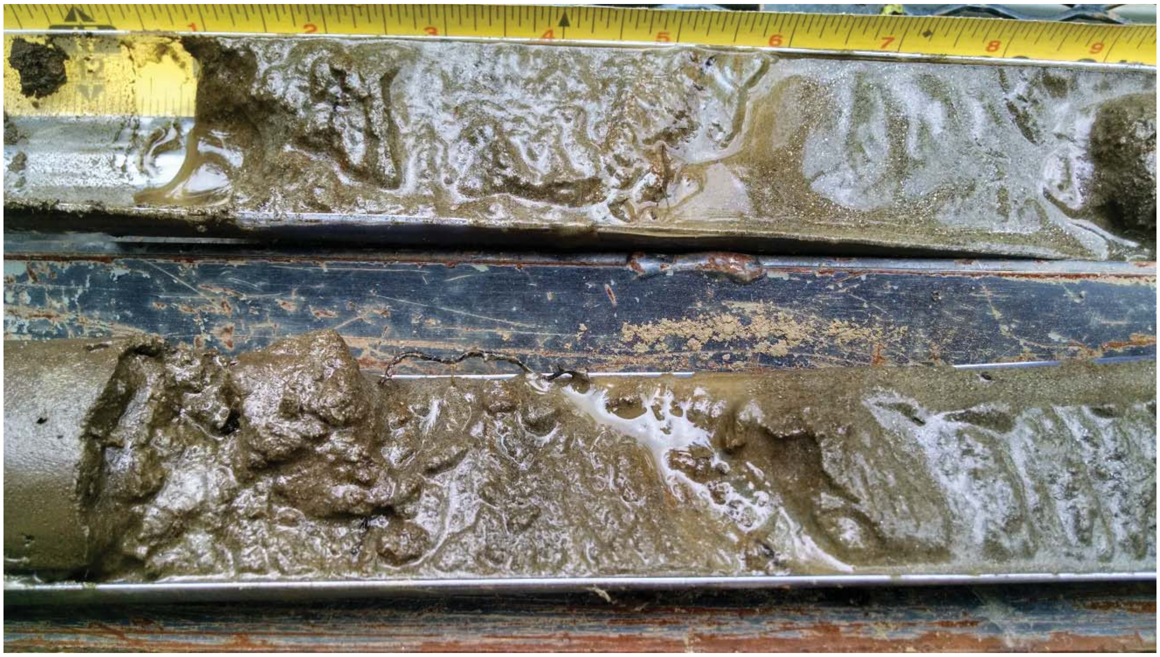
27 28 29 30 31 32 33 34 35 3F 36 37 38 39 40 41 42 43


37 38 39 40 41 42 43 44 45 46 47 4F 48 49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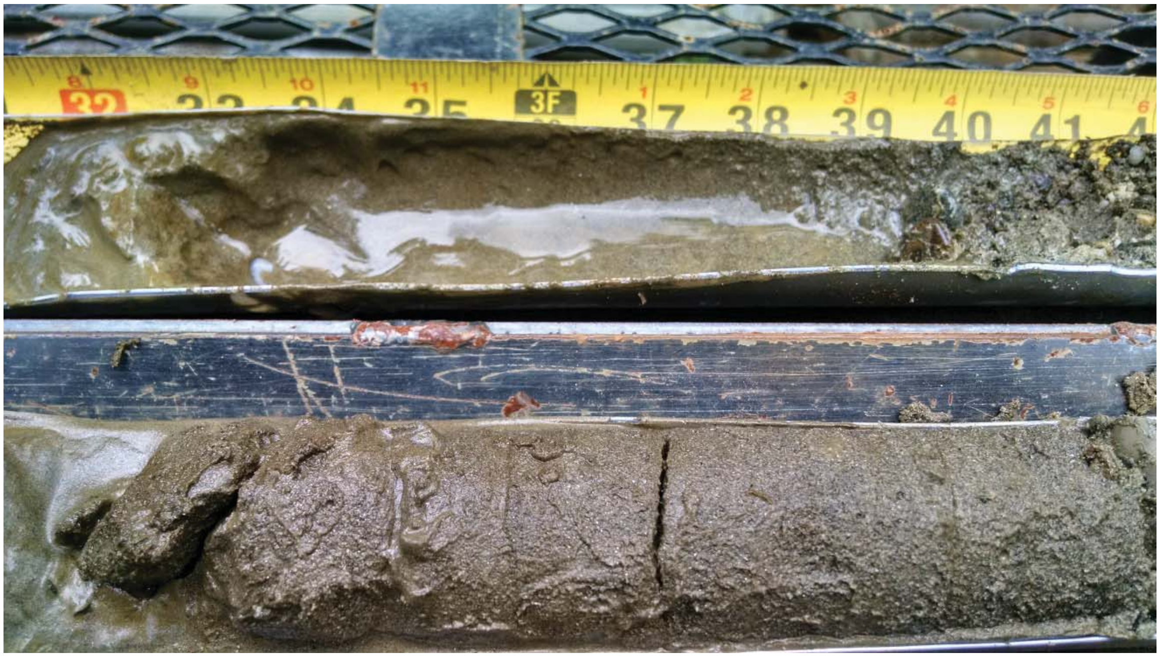
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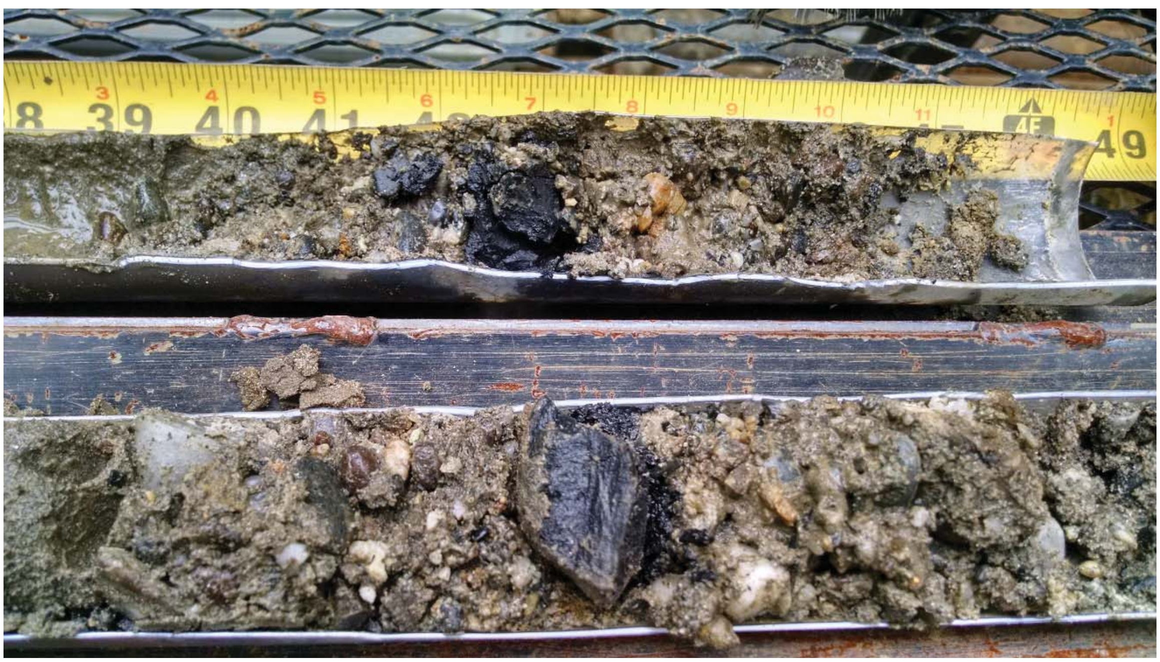
39
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Appendix B: Raw Data Used for Research

Eielson Station 1 Data 20 Sept 2017 C

Eielson Station 2 Data 20 Sept 2017 C

Frost probe and moisture data.xlsx

Edlund AFCEC Poster Compressed.

Points List.xlsx

Captain Edlund Survey.pdf

Zero Offset Data.xlsx

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The DoD is planning over $500M in military construction on Eielson Air Force Base (AFB) within the next three years. This construction program will expand the footprint of facilities and change parts of the storm water management scheme, which may have second order effects on the underlying permafrost layer. These changes in permafrost will drive engineering decision making at local and regional levels, and help shape the overall strategy for military readiness in the Arctic. Little site-specific knowledge exists on the human caused effects to permafrost at this location. In 2016, the permafrost degradation rates at Eielson AFB were modeled using the Geophysical Institute Permafrost Laboratory (GIPL) 2.1 model an

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Engineering, permafrost, arctic, Eielson, climate, climate change

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